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Tunnel Ventilation and Air Pollution Treatment

S. J. Rodgers, F. Roehlich, Jr.,
and C. A. Palladino

Mine Safety Appliance Research Corporation
Evans City, Pennsylvania 16033

June 30, 1970

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16. Abstract The dangers such as harmful physiological effects and nuisances for various tunnel air impurities for occupants were usually negligible, especially because of limited exposure periods. Only carbon monoxide, hydrocarbons, nitrogen oxides, and particulates pose any significant problems. From the foregoing analysis, standards of American Conference of Government and Industrial Hygienists, Federal ambient air and occupational safety and health regulations, and tunnel occupancy, tentative limits include:

	Safety for Unmanned Tunnels
Carbon Monoxide	500 ppm
Nitric Oxide	37.5 ppm
Nitrogen Dioxide	5 ppm
Particulates	10mg/meter^3

A computer program was developed and validated to predict various significant air contaminants. Instrumentation to monitor tunnel air quality was proposed. Treatments of tunnel air for either discharge to the surroundings or recycling were examined. Economic and processing constraints such as dilute concentrations were probed. Limited laboratory tests were conducted. Removal of carbon monoxide appears to be impractical. Adsorption of nitrogen dioxide and more noxious hydrocarbons by activated carbon showed promise. Particulates can be largely removed by electrostatic precipitation, filtration, and wet scrubbing.

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ABSTRACT

This study, funded by the Department of Transportation, Federal Highway Administration, was aimed at evaluating current air quality in existing tunnels and determining means of upgrading air quality in existing and future tunnels. The study consisted of six phases:

1. Identify the types and quantities of impurities in vehicular tunnels.
2. Evaluate the physiological effects of these impurities on tunnel workers and transients.
3. Establish air quality criteria for vehicular tunnels.
4. Determine available methods for improving air quality in vehicular tunnels.
5. Perform laboratory tests to demonstrate the applicability of selected purification procedures.
6. Recommend instrumentation for vehicular tunnels.

Phase 1 consisted primarily of a literature survey of past tunnel studies as well as vehicle emission rates as a function of various driving modes. Those of major concern are CO, NO_x, HC and particulates. A computer program was developed which adequately predicts the concentration of various impurities as a function of driving mode and ventilation rates. Some on-site sampling was performed to verify the validity of the computer program.

Phase 2 involved a survey of the literature to determine both short term and long term effects on humans exposed to specific tunnel impurities. These effects were considered in terms of both safe levels and comfort levels with respect to tunnel employees and tunnel transients.

The work of Phase 3 evolved as a result of the findings in Phase 2. Criteria for tunnel impurity levels were established with the basic guidelines being the Recommended Levels of the American Conference of Governmental

Industrial Hygienists, the EPA standards as set forth in the Federal Register and other references on the effects of air impurities on safety and comfort.

Phase 4 involved a review of current literature on methods and procedures for purification of contaminated atmospheres. Typical purification systems which were reviewed included catalytic combustion, adsorption, absorption, wet scrubbing and electrostatic precipitation. These methods were considered within the constraints imposed by tunnel atmospheres (i.e., low impurity levels and large gas volumes). An economic evaluation of selected systems was made.

Phase 5 required laboratory evaluation of the most promising methods of tunnel atmosphere purification. Small scale testing was performed in a chamber containing actual automobile exhaust gases. Parameters which were studied included temperature, space velocity, residence time and so on. Hopcalite at 225°F to 250°F reduced the CO to zero. Activated carbon proved to be effective in the removal of NO_2 and heavy hydrocarbons.

Phase 6 required the recommendation of impurity monitors which should be used in tunnels. For tunnels where the air quality is maintained by ventilation, the recommendation was made that CO continued to be monitored and used as the primary indicator of tunnel ventilation rates. It was also recommended that smoke meters be installed in tunnels, particularly those which have heavy diesel traffic.

TABLE OF CONTENTS

	Page No.
INTRODUCTION	1
RESULTS OF THE PROGRAM	3
Identification of Types and Quantities of Impurities in Vehicular Tunnels	3
Literature Survey	3
Computer Model	21
Emission Rates for CO, H-C, NO_x and Particulates	38
Verification of Computer Model	45
PHYSIOLOGICAL EFFECTS OF TUNNEL CONTAMINANTS	69
Contaminants Which Have Been Found in Tunnel Atmospheres	69
Selected Contaminant Levels for Vehicular Tunnels	72
Specific Limits for Manned Tunnels	72
Unmanned Tunnels	76
Summary of Recommended Levels	79
EVALUATION OF POLLUTANT REMOVAL METHODS	81
State of the Art - Applicable Control Technology	81
Applicable Tunnel Pollution Control Technology	83
Carbon Monoxide and Hydrocarbons	84
Catalytic Oxidation	87
Thermal Afterburning	93
Adsorption	94
Wet Scrubbing	97
Nitrogen Oxides	101
Source Control	105
Particulates	108
Tunnel Pollution Control - Feasibility and Economic Evaluation	113
Tunnel Pollution Control Strategies	116
Exhaust Emission Projections	119
Tunnel Air Treatment: Problem Statement	125
Tunnel Ventilation Costs	130
Process Feasibility: CO and Hydrocarbons	134
Process Feasibility: Hydrocarbons	139
Process Feasibility: Particulates	143
Process Feasibility: Water Solubles	150
General Feasibility: Recycle & Compartmentalization	151

TABLE OF CONTENTS (Continued)

	Page No.
Conclusions of Alternative Control Technologies	155
Selection of Control Techniques to be Evaluated	158
General Discussion	158
Carbon Monoxide Removal Systems	159
Hydrocarbons	159
Oxides of Nitrogen	159
Particulates	160
Purification Test System	160
Run No. 1 - Blank	162
Run No. 2 - Cold Hopcalite	164
Run No. 3 - Activated Carbon	164
Run No. 4 - Purafil	166
Run No. 5 - Hot Hopcalite	166
Run No. 6 - Silica Gel-Hopcalite	166
Run No. 7 - Hopcalite	167
Runs 8 and 9 - Filter Media	167
Run No. 10 - MnO_2-CuO	167
Run No. 11 - Charcoal Plus Hopcalite	167
Run No. 12 - Charcoal Plus Moisture Tolerant Hopcalite	168
Purification Systems for Tunnels	168
TUNNEL INSTRUMENTATION	171
Carbon Monoxide	171
Smoke or Haze	173
Other Monitors	174
Hydrocarbons	174
Nitrogen Oxides	174
Total Aldehydes	174
Carbon Dioxide and Oxygen	174
Recommendations for Tunnel Instrumentation	174
CONCLUSIONS	177
REFERENCES	181
BIBLIOGRAPHY	191
A. Specific Tunnel Studies	191
B. General Tunnel Studies	192
C. Emission Rates	194
D. Traffic Surveys and Studies	197
E. Ventilation Requirements and Equipment	199
F. Physiological Effects	201
G. Emission Control	204
H. Pollutant Monitoring	205

TABLE OF CONTENTS (Continued)

	Page No.
APPENDIX I - Final Report - IHF	209
APPENDIX II - **Pollutant Removal Process Calculations from Final Report--Patent Development Associates, Inc.**	241

LIST OF ILLUSTRATIONS

Figure No.		Page No.
1	Mean Hourly Traffic Flow Through Sumner Tunnel, By Time and Type of Day, Sept. 14-20, 1961	5
2	Mean Carbon Monoxide Concentration in Sumner Tunnel by Time and Type of Day, Sept. 14-20, 1961	6
3	Peak Carbon Monoxide Concentration in Sumner Tunnel, by Time of Day, July and September 1961	7
4	Mean Soiling Index at Sumner Tunnel Stations on Week Days, by Time of Day, Sept. 14-20, 1961	8
5	Mean CO Concentration at Sumner Tunnel Stations by Time of Day, April 20 Through 28, 1963	11
6	Mean Daily Concentration of Gaseous Pollutants in the Sumner Tunnel by Sampling Stations, April 20 Through 28, 1963	13
7	Carbon Monoxide Profile - Squirrel Hill Tunnel-North Tunnel	19
8	Carbon Monoxide Profile - Squirrel Hill Tunnel-South Tunnel	20
9	Carbon Monoxide Profile - Fort Pitt Tunnel-East Tunnel	22
10	Carbon Monoxide Profile - Liberty Tubes-West Tube	23
11	Effect of Air-Fuel Ratio on Automotive Exhaust Components	27
12	CO Output vs Vehicle Velocity	29
13	Multiplication Factor for Gradient (Increase / Decrease) For Gasoline Powered Cars	30

LIST OF ILLUSTRATIONS (Continued)

Figure No.		Page No.
14	Multiplication Factor for Gradient (Increase / Decrease) For Diesels	31
15	CO Emission at 5500 Ft. Compared with That at 500 ft.	32
16	Ventilation Rates and Roadway Gradient for Baltimore Harbor-East Tube	47
17	Actual Trace of CO Monitor Readings in The Baltimore Harbor Tunnel	48
18	Computer Predicted CO Profile-Baltimore Harbor Tunnel-East Tube	50
19	Calculated and Actual CO Concentration For Baltimore Harbor Tunnel-East Tube	51
20	Ventilation Rates and Roadway Gradient For Allegheny-North Tube	53
21	Computed Traffic Conditions for Armstrong Mountain Tunnel	54
22	Carbon Monoxide Profile Lincoln Tunnel-North Tube.	56
23	Actual and Calculated CO Values for the Lincoln Tunnel-North Tube	57
24	Actual and Calculated CO Values for the Lincoln Tunnel-Center Tube	59
25	Actual and Calculated CO Values for the Lincoln Tunnel-2 Way Traffic	60
26	Carbon Monoxide Profile of Fort Pitt Tunnel-West Tube	62
27	Measure of CO Values for the Naturally Ventilated Armstrong Tunnel	67
28	Schematic Diagram Proposed by Sir Bruce White	82
29	Emissions of Carbon Monoxide vs. Vehicle Speed	117

LIST OF ILLUSTRATIONS (Continued)

Figure No.		Page No.
30	Projected Average Exhaust Emissions, Period 1970-1980	126
31	Automotive Exhaust Purification Test Chamber	161
32	Removal of Hydrocarbons by Activated Carbon	165
33	Effect of Catalyst Temperature on CO Concentration	169

LIST OF TABLES

Table No.		Page No.
1	Suspended Particulate Parameters in Sumner Tunnel Outlet and Inlet Air, Sept. 14-20, 1961	10
2	Comparison of Mean Concentrations of Particulate Pollutants at Sumner Tunnel as Two-Way Tunnel, Sept. 14-20, 1961 With Operation as One-Way Tunnel April 20-28, 1963	12
3	Results of Tunnel Experiments, Summer 1958	15
4	Pollution in Blackwall Tunnel, May 14, 1959	16
5	Average Annual Amounts of Smoke and 7 Polycyclic Hydrocarbons Per 1000 Cubic Meters of Air at the Mersey Tunnel	17
6	Average Annual Amounts of Selected Impurities at the Mersey Tunnel	18
7	Exhaust Gas Emission Rates (ft^3/min	25
8	Carbon Monoxide Production as a Function of Carburetor Adjustment (Cubic Feet CO per Foot of Travel	26
9	CO Emissions Reported in Reference 22 Emission Rate gm CO/veh-mi	40
10	Grams of Pollutant Emitted per Mile For Fixed Mode of Operation (gm/veh-mi)	41
11	Carbon Monoxide Emission, gm CO/Vehicle-Mi.	42
12	Analysis of Material Collected From Ventilation Building of The Fort Pitt Tunnel	63
13	Fort Pitt Tunnel Test Data April 7, 1971	65
14	Measured Tunnel Contaminants	70

LIST OF TABLES (Continued)

Table No.		Page No.
15	TLV and STL for Selected Pollutants	77
16	Tentative Pollution Levels for Tunnels	79
17	Comparative Process Capabilities	85
18	Combustion-Related Vehicular Emissions	86
19	Removal Process Summary Catalytic Oxidation	89,90
20	Scrubber Capabilities (Imperato)	98
21	Results of a Typical Analysis of Automobile Exhaust Gases	103
22	Simplified Reaction Scheme for Photo-cehmical Smog	104
23	Suspended Particulate Parameters in Sumner Tunnel Outlet and Inlet Air, Sept. 14-20, 1961	110
24	National Air Quality Standards Proposed by EPA Primary Standards	120
25	Exhaust Emission Standards and Goals	122
26	Automobile Longevity	124
27	Tunnel Pollutant Loadings	127
28	Preliminary Single-Pollutant Optimum Process Indication	129
29	Estimated 1970 Tunnel Ventilation Blower Capital Costs as Function of Head Requirement	132
30	Operating Costs of Tunnel Ventilation Blower as Function of Head Requirement	133
31	Summary of Catalytic Oxidation Costs	139
32	Spray Holdup Time & Chamber Volume as Function of Dust Particulate Size	148

LIST OF TABLES (Continued)

Table No.		Page No.
33	Influence of Recycle on CO Concentration	154
34	Process Cost and Feasibility Summary	156
35	Summary of Purification Systems	163
36	Application of Continuous Monitoring Instruments to Tunnel Atmospheres	172

INTRODUCTION

This is the final report on Contract FH 11-7597 with the U. S. Department of Transportation, Federal Highway Administration. The work which covered Tunnel Ventilation and Air Pollution Treatment was performed by MSA Research Corporation and covered a period of 16 months. The basic objectives of the program were to identify the impurities and the level of these impurities in vehicular tunnels, establish the toxicity levels of these impurities and recommend desirable time-concentration limits for the impurities, determine and test applicable processes for removal of the impurities, and recommend air pollution monitoring devices for tunnels.

The work statement as presented in the contract is quoted below:

"The contractor shall furnish the necessary facilities, materials, personnel and such other services as may be required, and in consultation with the Government, conduct a research and development project entitled Tunnel Ventilation and Air Pollution Treatment.

The contractor shall direct its best efforts toward achievement of the program objective to the extent that time and funds are provided. The objective is to conduct research on the feasibility of removing impurities from the air within vehicular tunnels and to maintain a purity level so as to relieve the discomfort and eliminate the dangers to the traveling public without exhausting vitiated air to surrounding areas.

To fulfill the above objective, the contractor shall obtain through comprehensive literature surveys and other sources, pertinent information and analyze this material to:

1. Identify the types and quantities of impurities created by automotive traffic or resulting from combination of these impurities. Sources include automotive liquids, exhaust emissions, stray external sources, and tires, brake bands, etc.

Recognized variables include traffic conditions and vehicle mix under various circumstances such as speed, load and, fuel type; road conditions including gradient, pavements, and elevation above mean sea level; and atmospheric conditions such as ambient temperature and winds at portals.

2. Classify each impurity generated by vehicular traffic into a category which will identify the effect of each impurity upon the various tunnel users. For each, the degree of toxicity, irritation, visibility reduction, or odor shall be established with consideration of concentration levels and exposure times.

3. Establish criteria for desirable and allowable time-concentration limits of the pertinent impurities for the maintenance of a safe and comfortable tunnel atmosphere for various conditions and with due consideration to operating personnel as well as the traveling public. Reasoning behind the criteria shall be formulated.

4. Determine available methods, processes, and mechanisms for removing contaminants from the tunnel air which may include but not be limited to cooling, scrubbing, electrostatic precipitation, and deacidification. The interplay of natural additions and flow, vehicle induced air movement, internal ventilation patterns, and exhausting to the atmosphere shall be considered. Physical feasibility of the systems including power, space, and disposal problems shall be included in the analyses. Cost effectiveness, and other economic factors will be involved in arriving at practical and practicable systems for various tunnel conditions.

5. Investigate and establish the adequacy, practicability, reliability, and costing of available air pollution gauges and detection devices (and systems of these) in the tunnel environment. The local concentrations as well as the large scale concentrations of pollutants shall be subject to measurement.

6. Perform laboratory tests as required to demonstrate the applicability of chosen clean up procedures. This phase of the work must be carefully considered so that unnecessary work is not expended."

Two subcontractors were used in the performance of the program. The Industrial Health Foundation of Pittsburgh, Pennsylvania contributed in evaluating the physiological effects of tunnel impurities. Patent Development Associates, Inc. of Glenshaw, Pennsylvania reviewed current impurity control technology and performed feasibility and economic evaluations of the current technology.

RESULTS OF THE PROGRAM

This section presents the results of the various phases of the program. One of the more difficult tasks was to recommend desirable time-concentration limits for vehicular tunnels. These recommendations were to cover three general categories - safe levels for tunnel personnel (Maintenance men or police officers) who would spend hours per day in a tunnel, safe levels for transient users who would spend 5-15 minutes in a tunnel and comfort levels for the transient users.

Identification of Types and Quantities of Impurities in Vehicular Tunnels

Literature Survey - All artificially ventilated tunnels have instrumentation for continuous monitoring of CO. In almost every case, the type of instrument which is used to monitor CO in vehicular tunnels is the Hopcalite type where the change in temperature due to the heat of catalytic oxidation of CO can be related to the CO concentration in the air samples. Although a wealth of data exists on CO concentration as a result of this continuous monitoring, it is difficult to relate the CO concentration to the traffic density, type of vehicles (gasoline or diesel), vehicle velocity and so on since these parameters are not routinely measured. Furthermore, the monitoring systems in tunnels measure only CO, while this program is directed toward establishing typical concentration values for other impurities which are present in vehicular tunnels. One additional shortcoming to this information is that it represents point concentrations either at the site of the analyzer or an average concentration for a complete tunnel section when the monitoring station is located in a ventilation duct.

A number of studies have been made on the concentration of impurities other than CO in vehicular tunnels. Some studies have been devoted to measuring the complete CO profile throughout the length of a tunnel. These studies were helpful in trying to determine typical and maximum values of impurities in tunnels, but again in many cases the studies failed to present real time data on traffic patterns and ventilation rates.

Two studies were made on the 1.1 mile long Sumner Tunnel in Boston, Massachusetts. The first study was made in 1961[1] when the Sumner Tunnel was a single tube carrying two way traffic. A second study on the Sumner Tunnel was performed in 1963[2] when a sister tunnel, the Callahan Tunnel was opened and the Sumner Tunnel was converted to

a two lane, one way traffic pattern. The Sumner Tunnel has intake and exhaust fans located at both the Boston and East Boston ventilation buildings. The ventilation rate ranged from 73,000 cfm to 613,000 cfm.

During the first study, the number of vehicles using the tunnel was about 35,000 per day. The minimum vehicle flow was 200 vehicles per hour at 5 A.M. and the maximum flow was 2,200 vehicles per hour during the morning and evening rush hours (8 A.M. and 4 P.M.). Figure 1 is a plot of traffic flow versus time of day for a typical weekday, weekend and weekly average for the week of September 14 to September 20, 1961. Figure 2 shows the mean CO concentration in the tunnel exhaust stack for the same period of time. Figure 3 shows the peak CO concentration for the week of September 14-20, 1961 as well as the week of July 27-August 2, 1961. The highest instantaneous peak concentration during the study was 256 ppm. The tunnel is essentially a closed system and thus offers the opportunity to determine the amount of pollution emitted per vehicle mile using the equation:

$$\text{Amount measured} = \frac{(\text{Outlet conc.} - \text{Inlet conc.})(\text{Volume of ventilation air})}{(\text{No. of vehicles})(0.55 \text{ mile of tunnel length})} \quad (1)$$

The term 0.55 mile was used since only half of the tunnel served by the Boston ventilation building was used in the calculation. From 1 A.M. to 5 A.M. the calculated emission rate for CO was 35 gm per vehicle mile. During the remainder of the day, the values for emission rate were approximately twice this value. The higher rate is due to the effect of traffic modes, varying periods of idle, acceleration and deceleration as a result of traffic tie-ups.

The mean soiling index was measured, also, and is shown in Figure 4. The highest mean coefficient of haze and smoke (Cohs) per 1000 feet of air was 6.5 Cohs. In Allegheny County, Pennsylvania the following classifications are used for soiling index:(3)

0-1.0 Cohs/1000 ft = slight pollution
1.0-2.0 Cohs/1000 ft = moderate pollution
2.0-3.0 Cohs/1000 ft = heavy pollution
3.0-4.0 Cohs/1000 ft = very heavy pollution

Thus, in terms of this arbitrary assignment of pollution values, the 6.5 Cohs/1000 ft measured in the Sumner Tunnel would correspond to very heavy pollution.

Suspended particulates were measured over a sampling period of 8 hrs with the maximum concentration being observed during the period from 9 A.M. to 3 P.M. The total particulate

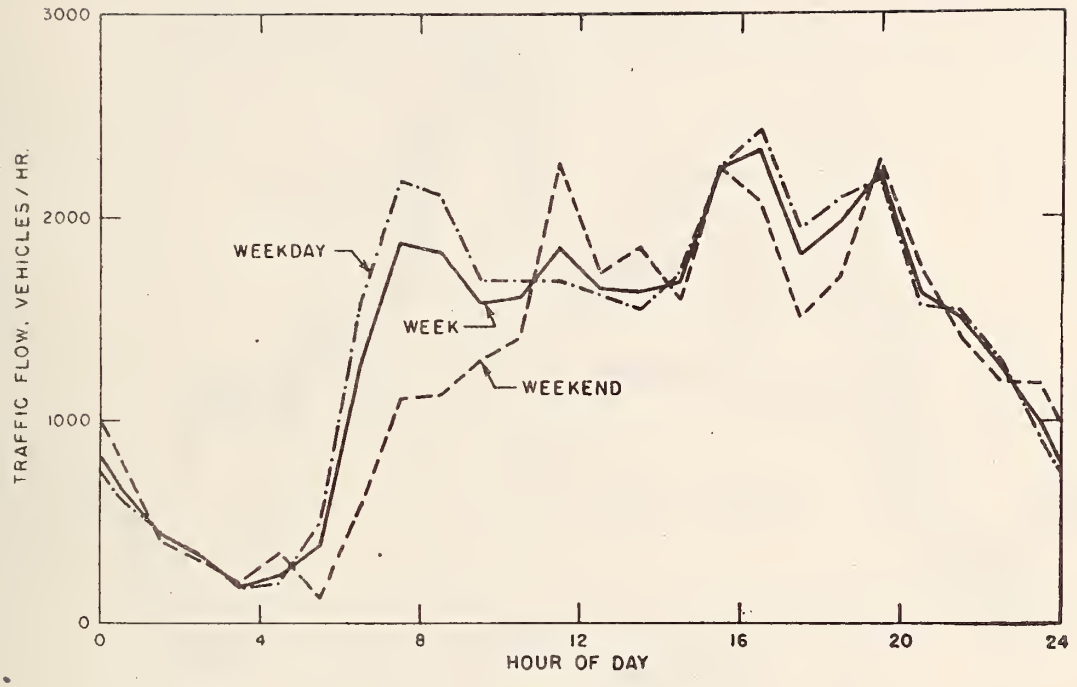


FIGURE 1 - MEAN HOURLY TRAFFIC FLOW THROUGH SUMNER TUNNEL, BY TIME AND TYPE OF DAY, SEPT. 14-20, 1961

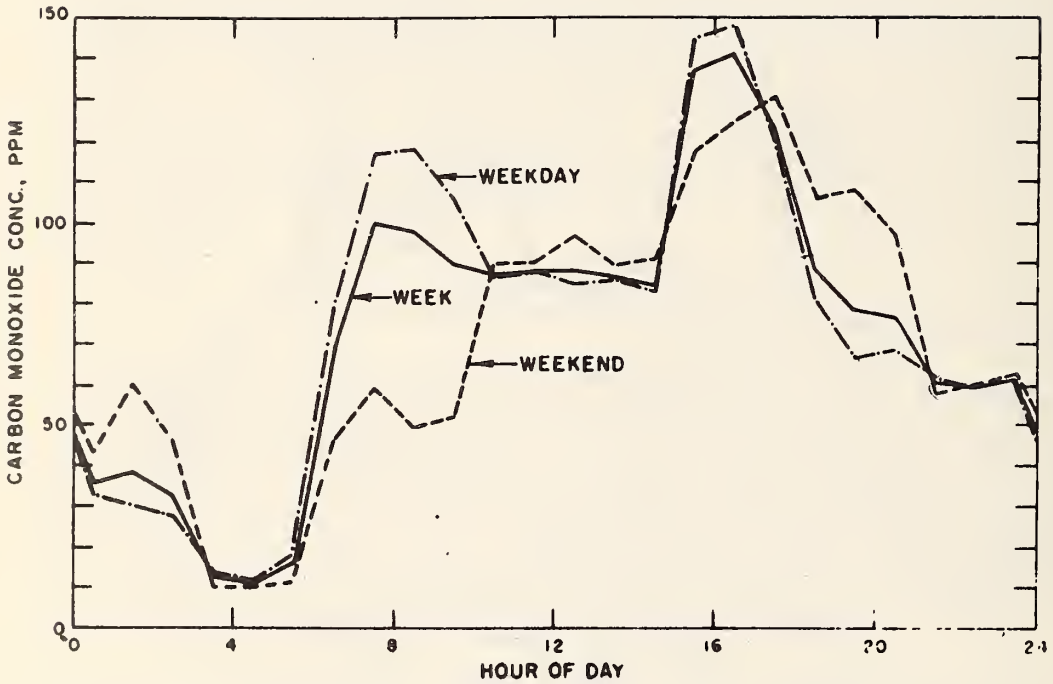


FIGURE 2 - MEAN CARBON MONOXIDE CONCENTRATION IN SUMNER TUNNEL BY TIME AND TYPE OF DAY, SEPT. 14-20, 1961

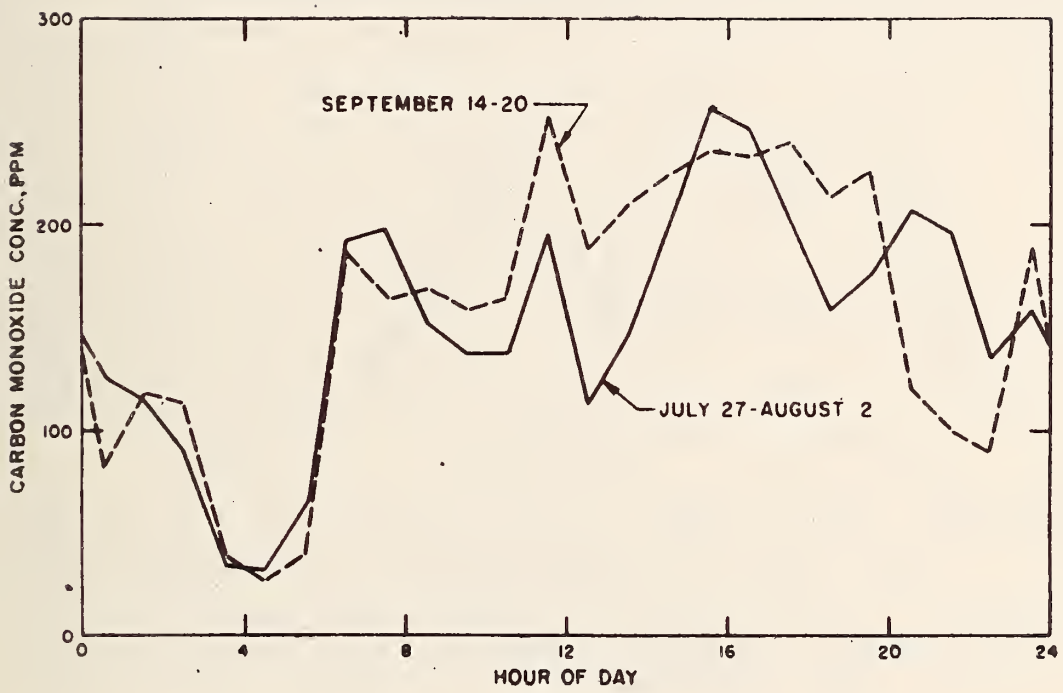


FIGURE 3 - PEAK CARBON MONOXIDE CONCENTRATION IN SUMNER TUNNEL, BY TIME OF DAY, JULY AND SEPTEMBER 1961

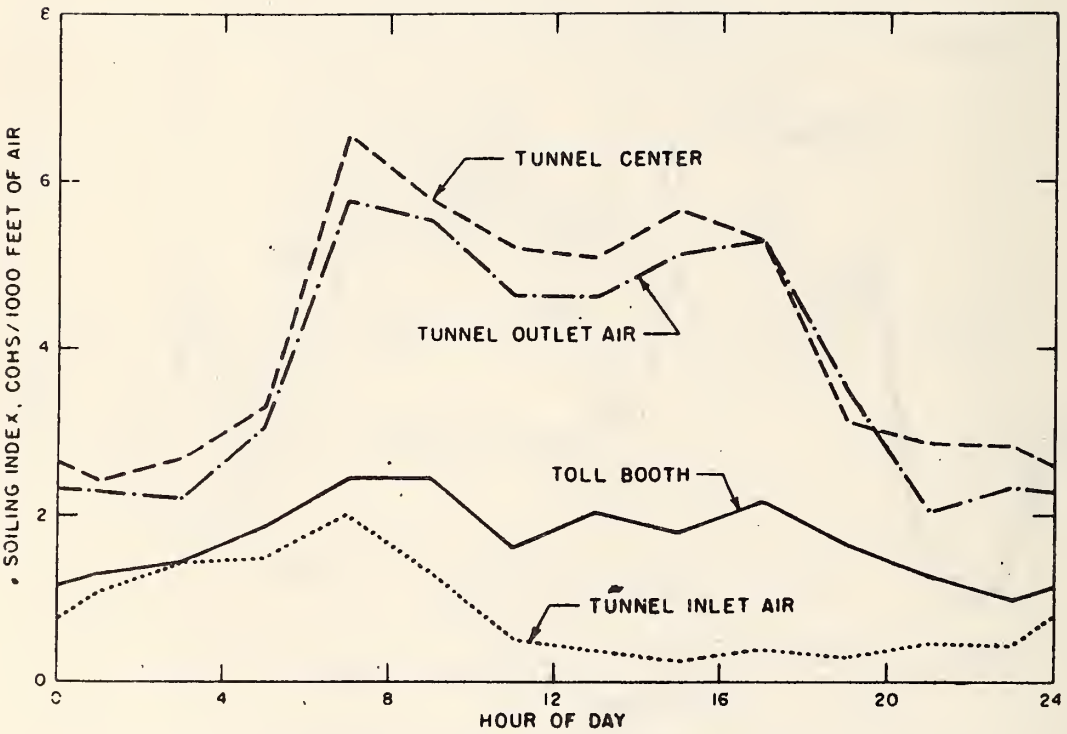


FIGURE 4 - MEAN SOILING INDEX AT SUMNER TUNNEL STATIONS ON WEEK DAYS, BY TIME OF DAY, SEPT. 14-20, 1961

concentration during that period was ∿0.6 mg/m^3. Benzene soluble material (organics) accounted for about 40% (0.24 mg/m^3) of the total particulate inventory. Lead accounted for 7.5% (.045 mg/m^3) of the total suspended particulates. The balance of the particulates were sulfates, nitrates and metals other than lead. Cadmium, a metal of particular concern due to its toxicity, was quite low at 0.01 mg/m^3. Table 1 lists the composition of the collected particulate material. Using equation (1) emission rates were calculated for particulates (0.36 gm/vehicle mile), organic particulates (0.16 gm/vehicle mile) and lead (0.031 gm/vehicle mile).

The second Sumner Tunnel study involved a total of 6 sampling stations throughout the tunnel.(2) This study was made after the tunnel had been converted to a two lane, one way traffic configuration with an average daily traffic density of 22,000 vehicles per day. A significant decrease in impurity levels was noted; the decrease was attributed to operation of the tunnel in a one way traffic mode and a decrease of 36% in motor vehicle traffic. Figure 5 shows the CO concentration as a function of time of day. Mean morning rush hour concentrations for the two way mode ranged from 100-120 ppm CO, while the one way mode mean concentration was ∿90 ppm CO. The soiling index was also lower showing 3.5 Cohs for one way traffic versus 6.5 Cohs for two way traffic. Table 2 compares the mean particulate concentration for the two modes of traffic.

Additional pollutants including SO_2, NO_2, aldehydes and NO were measured during the second study. The concentrations of these impurities are shown in Figure 6. It was concluded that automotive exhaust does not contribute significantly to the SO_2 content of tunnel air. The results showed that the ratio of NO/NO_2 was approximately 5/1. Finally, the aliphatic aldehydes ranged from about 0.01 to 0.1 ppm.

An early study on the CO and particulate levels in the Holland Tunnel was performed by the Bureau of Mines.(4) The data in this report is probably of limited value due to the difference in emission rates from gasoline powered vehicles, gasoline composition and the number of diesel powered vehicles of today compared with the types of vehicles in use at that time. Standard operating procedure at that time was to allow the CO concentration to rise to 250 ppm with no change in ventilation rate. If the level remained at 250 ppm for longer than 5 minutes, then additional fans were activated. The authors noted at that time that the CO concentration was highest on the upgrade sections of the tunnel.

TABLE 1 - SUSPENDED PARTICULATE PARAMETERS IN SUMNER TUNNEL OUTLET AND INLET AIR, SEPT. 14-20, 1961

Type of Suspended Particulate	Concentration (Nanograms/Cu Meter)			Ratio	Estimated Relative Importance of Motor Vehicles on Outdoor Conc.		Amount Measured per Vehicle-Mile of Tunnel Travel	Total Amount for 1 Day of Tunnel Operation
	Outlet	Inlet	Difference Outlet−Inlet	Outlet / Inlet	Index (Outlet/Inlet − 1)	Rank	(μG/Vehicle-Mile)	(Gm./Da.)
Total	588,000	104,000	484,000	5.7	4.7	8	358,500	13,519
Sulfate	29,300	22,200	7,100	1.3	0.3	15	5,260	192
Nitrate	2,400	3,400	−1,100	0.7	0		0	0
Total organics (benzene sol.)	225,000	11,000	214,000	20.4	19.4	5	158,500	5,977
Benzo(a)pyrene	690	2.6	687	265	264	2	491	18
Benzo(g,h,i)-perylene	990	4.7	985	211	210	3	704	26
Coronene	530	1.4	529	378	377	1	377	14
Metals								
Antimony	170	153	17	1.11	0.11	18	12	0.45
Beryllium	4.3	4.1	0.2	1.05	0.05	20	0.13	0.005
Bismuth	5.5	4.9	0.6	1.12	0.12	17	0.42	0.016
Cadmium	38	28	10	1.36	0.36	14	7.2	0.27
Chromium	128	87	41	1.47	0.47	13	29.1	1.09
Cobalt	22	20	2	1.10	0.10	19	1.3	0.05
Copper	278	67	211	4.15	3.15	9	151	5.6
Iron	23,397	2,264	21,133	10.33	9.33	6	15,094	565
Lead	44,500	1,100	43,400	40.5	39.5	4	31,000	1,160
Nickel	112	120	−8	0.93	0		0	0
Manganese	133	50	83	2.66	1.66	11	59	2.2
Molybdenum	60	17	43	3.53	2.53	10	31	1.2
Tin	154	133	21	1.16	0.16	16	15	0.56
Titanium	472	70	402	6.74	5.74	7	287	11
Vanadium	278	325	−47	0.86	0		0	0
Zinc	2,248	1,523	725	1.48	0.48	12	518	20

Note: The above are mean values for the entire sampling period. All analyses except lead were performed on glass-filters.[2,3] Lead values are from millipore filter samples analyzed by wet chemical techniques. All metal values except lead were obtained by emission spectrometry.

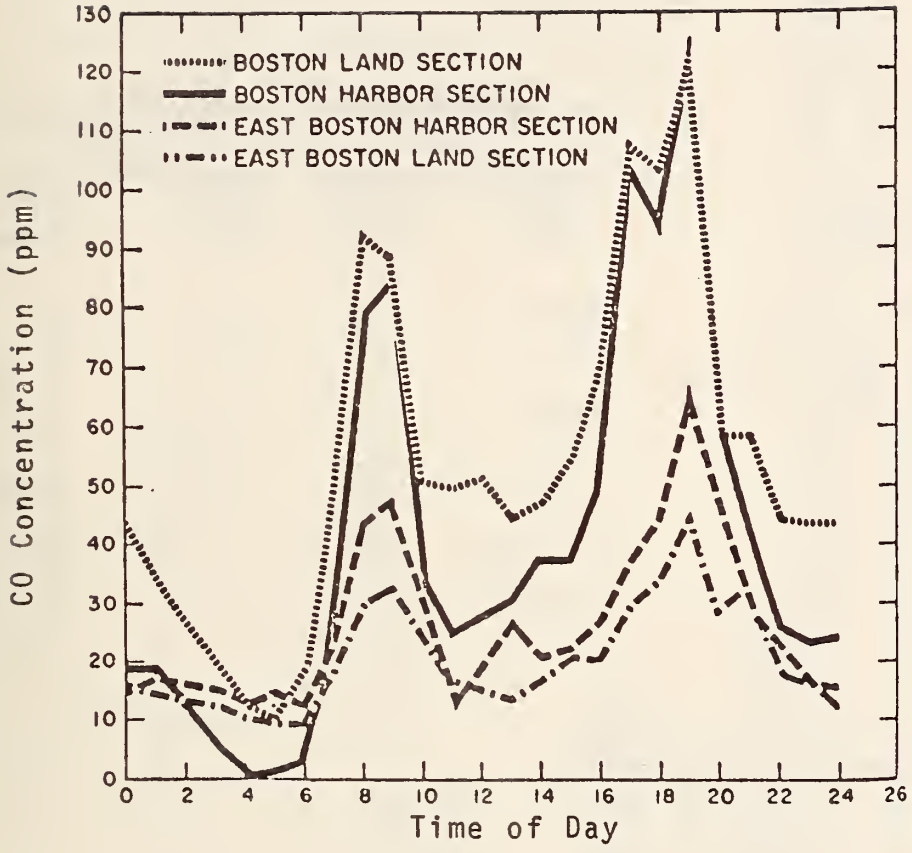


FIGURE 5 - MEAN CO CONCENTRATION AT SUMNER TUNNEL STATIONS BY TIME OF DAY, APRIL 20 THROUGH 28, 1963

TABLE 2 - COMPARISON OF MEAN CONCENTRATIONS OF PARTICULATE POLLUTANTS AT SUMNER TUNNEL AS TWO-WAY TUNNEL, SEPT. 14-20, 1961 WITH OPERATION AS ONE-WAY TUNNEL APRIL 20-28, 1963

Pollutant	Concentration, µg/cu m			
	Two-Way Tunnel		One-Way* Tunnel	
	Outlet Air	Inlet Air	Outlet Air	Inlet Air
Total particulates	588	104	424	86
Benzene-soluble organic substances	225	11	144.2	8.3
Sulfates	29	22	18.1	0.3
Nitrates	2.4	3.4	0.3	0.9
Lead	44.5	1.1	9	0.1

*36% decrease in traffic

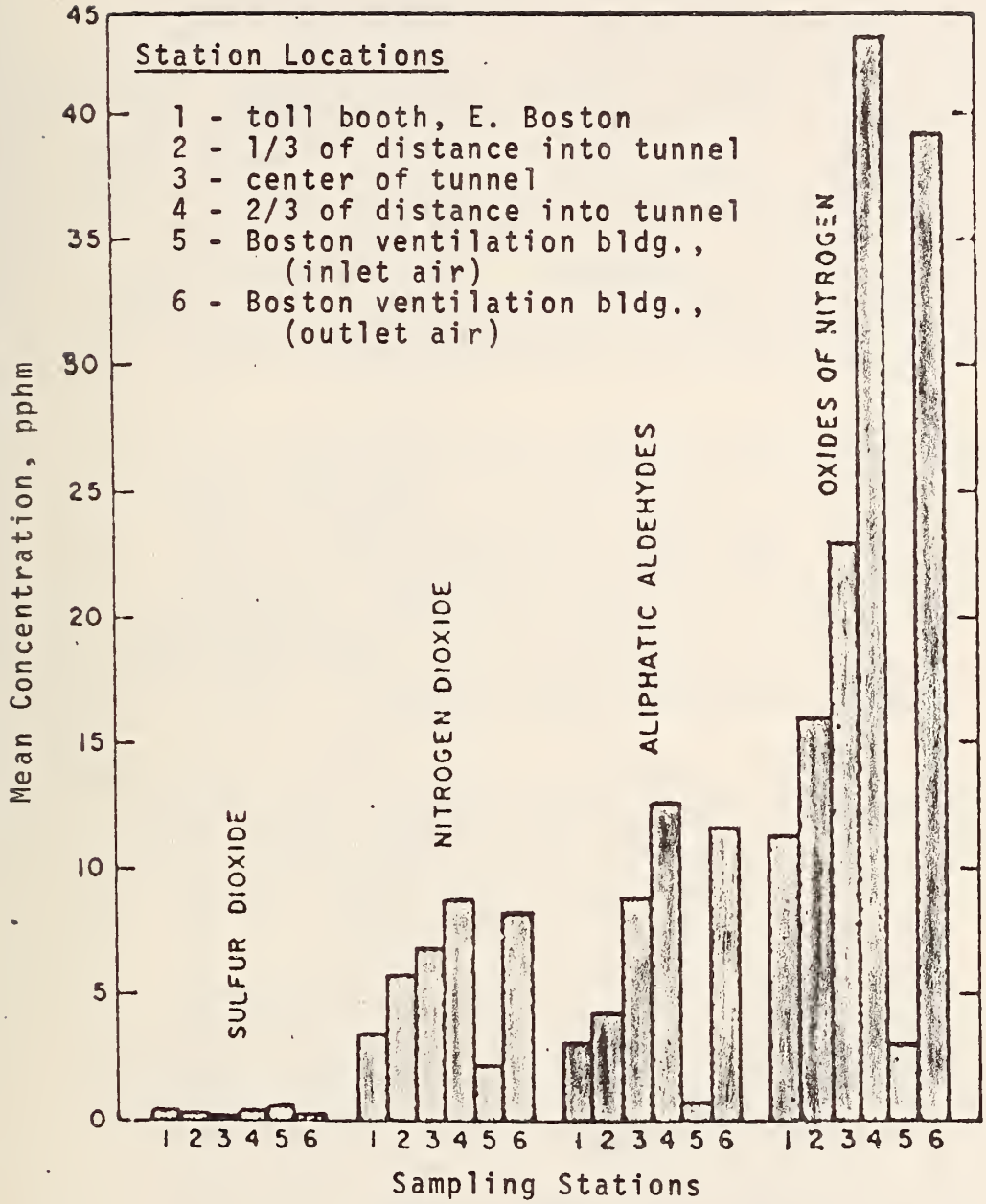


FIGURE 6 - MEAN DAILY CONCENTRATION OF GASEOUS POLLUTANTS IN THE SUMNER TUNNEL BY SAMPLING STATIONS, APRIL 20 THROUGH 28, 1963

Work done by Katz and Frevert[5] led to an estimate of CO emission rate of 10 cu ft per car while traversing the tunnel. This would correspond to an emission rate of 220 g CO per vehicle mile, a factor of approximately 10 higher than the currently accepted average emission rate. Particulate concentration in the tunnel ranged up to 1.88 mg/m^3 with a mean particle diameter of less than 1 micron. Analyses of the particulates showed lead and arsenic to be present, but it was concluded on the basis of inlet air concentrations that arsenic was not contributed by automotive exhaust. One other point of interest in this study was a reference to Singstad's work[6] on the induced piston effect of automotive traffic in vehicular tunnels. Singstad stated that 1000 vehicles per hour produced longitudinal air velocities of 880 ft/min. Assuming a free cross-sectional area of 370 ft^2, this is equivalent to a volumetric flow of 315,000 cfm.

Waller, et al[7] studied the impurity levels of the Blackwall and Rotherhithe Tunnels in London during a period of high traffic density. Table 3 summarizes the concentration of CO, smoke and hydrocarbons which were found in the two tunnels. Table 4 summarizes additional tests which were made in the Blackwall Tunnel only and includes lead, NO and NO_2 in addition to the previously mentioned contaminants. It was reported that the mass median diameter of the smoke particles was 1 micron.

Stocks et al[8] studied the concentration of seven polycyclic hydrocarbons and 13 trace metals in the Mersey Tunnel in England. Table 5 shows the average annual concentration of smoke and selected hydrocarbons found in the Mersey Tunnel. Table 6 lists the average annual concentrations for the 13 metals which were analyzed.

A recent study was performed on the three artificially ventilated tunnels in Pittsburgh by the Michael Baker, Jr. Company[9-11]. Although this study was limited to measurement of CO only, it is of interest because the CO profile throughout each tunnel was measured experimentally and one can compare the CO levels at various points in the tunnel with the levels indicated by the permanently installed CO monitoring systems. Figure 7 shows the CO profile of the 4225 ft long Squirrel Hill westbound tunnel during the early morning rush hour. The maximum value indicated by the tunnel CO monitors was 100 ppm CO whereas levels as high as 160 ppm were measured near the center of the tunnel. Figure 8 shows the effect of two way traffic in a tunnel wherein the piston effect is negated. Again the maximum CO monitor reading (145 ppm CO) was signifi-

TABLE 3 - RESULTS OF TUNNEL EXPERIMENTS, SUMMER 1958

	Blackwall Tunnel								Rotherhithe Tunnel	Merton Garage
	July 3, 1958		August 1, 1958			August 4, 1958	August 20, 1958		September 14, 1958	June 21, 1956
Time	08·45-09·45	09·50-10·50	16·00-17·15	17·33-18·33	18·38-19·38	19·30-22·00	08·30-09·36	09·38-10·32	21·00-22·42	23·00-01·00
Traffic flow*: Petrol	919	631	1,037	1,228	1,054	1,552	1,136	896	1,439	—
Diesel	272	233	228	210	140	55	335	312	125	—
Speed (m.p.h.)	—	—	—	1·7	2·9	4·1	2·0	2·8	16·2	—
Traffic density†:										
Petrol	—	—	—	60	30	31	47	26	20	—
Diesel	—	—	—	10	4	1	14	9	2	—
Carbon monoxide (p.p.m.)	295	—	—	200	—	138	—	70	170	—
Smoke (mg./100 m.³)	235	174	133	162	116	93	157	179	191	144
Hydrocarbons, µg./100m.³ air:										
Fluoranthene	73	66	29	38	21	42	35	27	54	10
1 : 2-benzpyrene	19	16	9	16	10	11	11	12	17	2
Pyrene	119	100	43	62	30	60	52	39	81	17
Coronene	35	33	17	34	25	22	22	21	30	—
Anthanthrene	16	17	6	17	12	13	11	9	18	—
1 : 12-benzperylene	53	53	19	57	42	36	40	37	55	2
3 : 4-benzpyrene	29	26	14	24	12	18	17	16	27	3
Hydrocarbons, µg./g. smoke:										
Fluoranthene	308	381	216	233	184	434	225	151	283	69
1 : 2-benzpyrene	80	95	69	98	87	117	71	68	89	17
Pyrene	505	578	324	387	257	628	328	216	425	120
Coronene	150	191	125	213	215	228	142	116	155	—
Anthanthrene	67	97	44	102	106	132	70	52	94	—
1 : 12-benzperylene	225	307	140	352	361	377	352	208	295	13
3 : 4-benzpyrene	123	151	109	146	101	186	111	91	141	18

*Vehicles per hour in both directions.
†Estimate of number of vehicles in relevant ventilation section (see text).

TABLE 4 - POLLUTION IN BLACKWALL TUNNEL, MAY 14, 1959

	Time (hours)								
	10-	11-	12-	13-	14-	15-	16-	17-	18-19
Traffic flow*: Petrol	702	674	611	631	756	780	1,018	1,241	1,196
Diesel	346	362	326	284	324	311	286	211	194
Speed (m.p.h.)	5·5	7·4	11·1	9·1	6·0	8·7	7·9	5·4	6·3
Traffic density†: Petrol	14·6	10·3	6·3	7·5	14·3	10·2	14·7	26·2	21·6
Diesel	7·2	5·5	3·4	3·4	6·1	4·1	4·1	4·5	3·5
Carbon monoxide (p.p.m.)	76	64	39	35	81	66	92	120	103
Smoke (mg./100 m.^{3})	268	319	216	169	200	177	204	202	177
Lead (μg./m.^{3})	23·8	18·7	11·4	9·2	18·8	13·4	19·0	27·2	22·0
Nitric oxide (p.p. 100 m.)	87	133	97	91	137	103	80	121	103
Nitrogen dioxide (p.p. 100 m.)	3	10	7	6	7	7	5	10	7
Hydrocarbons, μg./100 m.^{3} air:									
Fluoranthene	160	125	109	84	95	81	94	110	79
1 : 2-benzpyrene	24	24	17	14	19	13	17	18	16
Pyrene	139	137	83	66	82	68	80	98	73
Coronene	20	14	7	5	17	10	13	22	21
Anthanthrene	15	26	10	12	9	9	11	7	6
1 : 12-benzperylene	48	40	24	15	41	26	31	51	45
3 : 4-benzpyrene	47	47	32	27	33	23	29	31	27
Hydrocarbons, μg./g. smoke:									
Fluoranthene	597	393	505	495	474	458	465	547	448
1 : 2-benzpyrene	88	75	78	80	94	76	83	89	89
Pyrene	519	430	385	388	408	382	394	487	415
Coronene	75	44	34	27	87	55	64	109	117
Anthanthrene	57	83	48	73	47	50	55	36	35
1 : 12-benzperylene	178	126	111	87	206	148	151	252	252
3 : 4-benzpyrene	176	147	148	157	166	128	142	151	153

*Vehicles per hour in both directions.
†Estimate of number of vehicles in relevant ventilation section (see text)

TABLE 5 - AVERAGE ANNUAL AMOUNTS OF SMOKE AND 7 POLYCYCLIC HYDROCARBONS PER 1000 CUBIC METERS OF AIR AT THE MERSEY TUNNEL

Location of Filter	Total smoke (mg)	3:4 Benz-pyrene	1:12 Benz-perylene	Pyrene	Fluor-anthene	1:2 Benz-pyrene	Coro-nene	Anth-anthrene
St. George's Dock	262	31	26	7	23	22	6	6
Roe Street	271	34	30	10	12	19	7	6
Edge Lane	331	38	41	18	24	26	8	9
Inside Bus Depot	346	49	43	19	26	32	8	11
Inside Motor Garage	427	45	48	16	22	30	12	14
Mersey Tunnel								
Mid-point	710	37	81	22	19	22	50	9
Road junction	1588	53	137	44	37	36	75	16

TABLE 6 - AVERAGE ANNUAL AMOUNTS OF SELECTED IMPURITIES AT THE MERSEY TUNNEL

Location of Filter	mg/1000 m^3		μg/1000 m^3											
	Total ash	Lead	Zinc	Copper	Titanium	Arsenic	Manganese	Nickel	Antimony	Vanadium	Chromium	Molybdenum	Cobalt	Beryllium
St. George's Dock	24.5	0.55	250	74	9	40	28	19.0	15.5	53.5	5.4	3.15	2.20	0.58
Roe Street	19.5	1.99	260	46	54	45	18	55.5	20.0	18.0	6.7	2.95	2.65	0.42
Edge Lane	17.0	0.60	325	50	44	31	17	96.0	11.0	13.0	4.7	2.45	1.80	0.38
In Bus Depot	17.5	0.61	260	47	68	40	18	13.9	10.0	23.5	5.1	3.25	1.45	0.54
In Motor Garage	10.5	1.29	175	41	30	37	18	7.8	10.1	23.5	2.9	2.45	0.95	0.31
Mersey Tunnel														
Mid point	54.5	7.30	325	120	19	36	53	15.5	14.5	27.0	7.5	1.90	4.85	0.71
Road junction	120.5	20.45	600	205	38	66	104	30.5	21.5	48.0	14.5	3.40	4.35	1.60

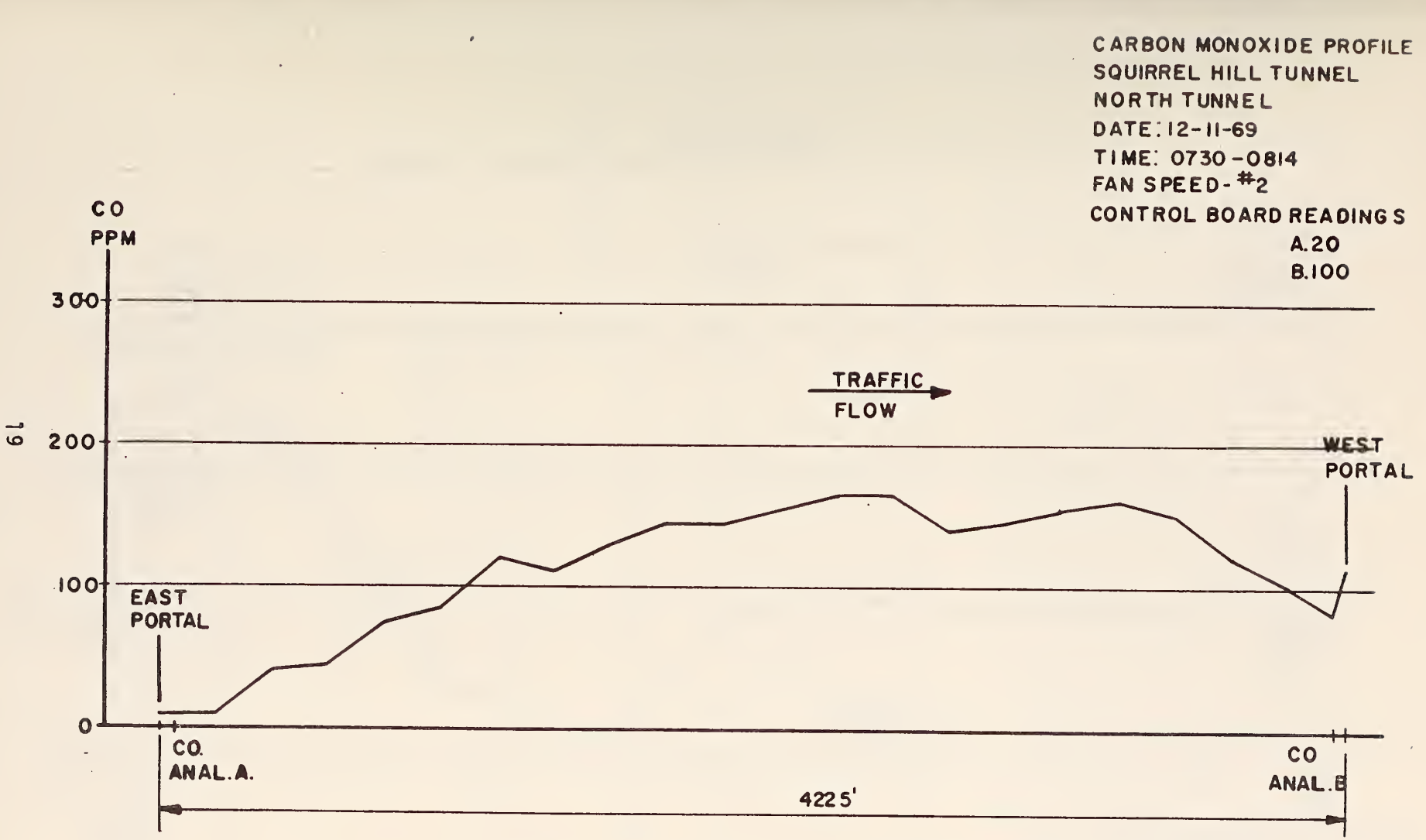


FIGURE 7 - CARBON MONOXIDE PROFILE - SQUIRREL HILL TUNNEL
NORTH TUNNEL

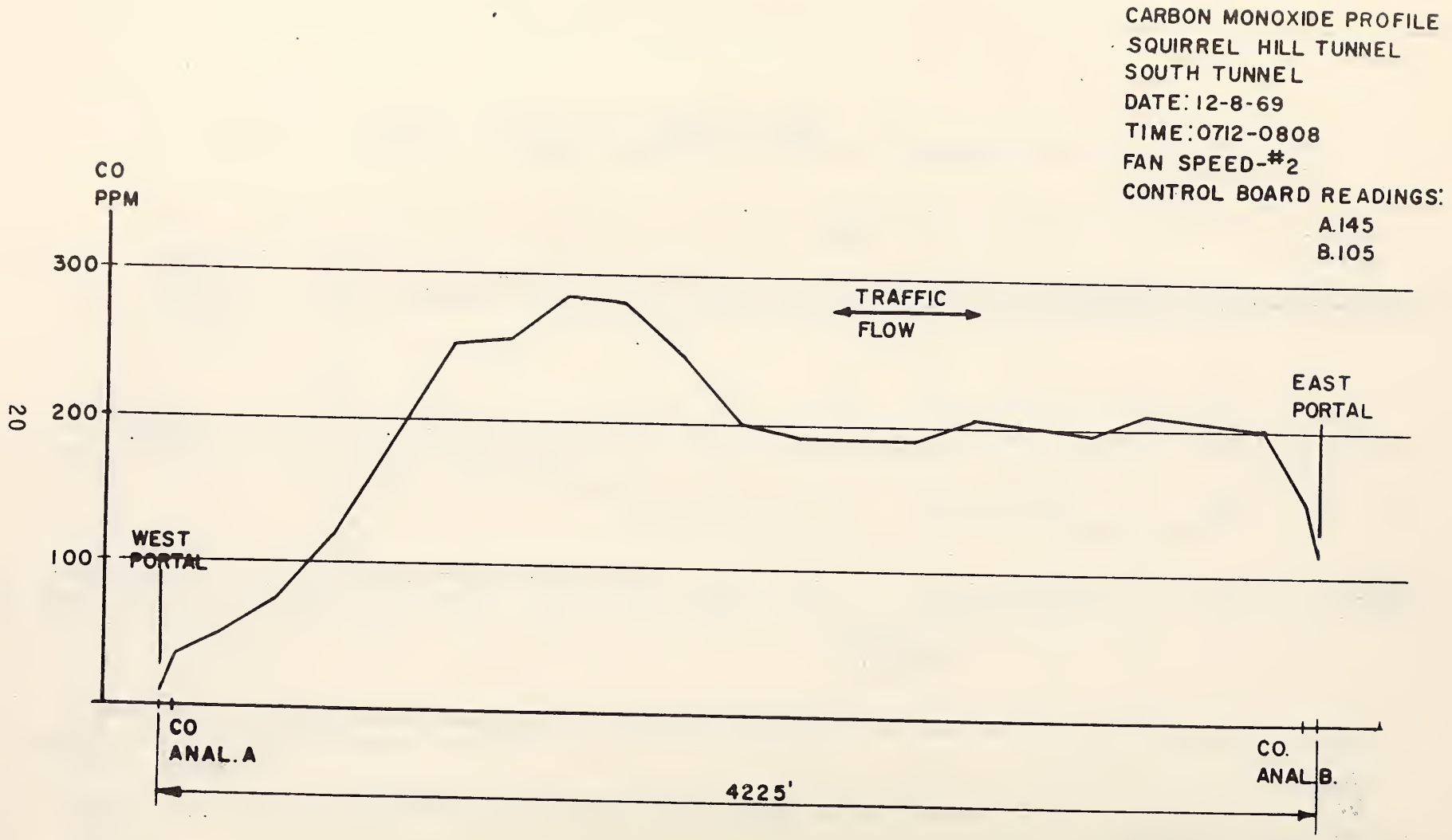


FIGURE 8 - CARBON MONOXIDE PROFILE - SQUIRREL HILL TUNNEL
SOUTH TUNNEL

cantly lower than the actual maximum in the tunnel (290 ppm CO). Figure 9 shows the CO profile of the 3613 ft long Fort Pitt Tunnel during the early morning rush hour. In this case, the maximum reading of the CO monitor was 150 ppm CO while the maximum CO concentration in the tunnel was 195 ppm CO. Figure 10 is a CO profile of the Liberty Tunnel during the evening rush hour. The Fort Pitt and Squirrel Hill Tunnels have a longitudinal distributive type of ventilation while the Liberty Tunnel has a basic longitudinal type of ventilation. Specifically, fresh air is drawn in through the entry portal and exhausted at the center for the first half of the tunnel, then fresh air is injected about 50 ft beyond the center and exhausted through the exit portal. This mode of ventilation accounts for the CO peak at the center of the tunnel.

Computer Model - After having reviewed the pertinent literature, two facts became obvious. First, the bulk of the work on tunnel impurity levels had been limited to the measurement of CO, and second the bulk of the data which had been reported represented averages over time periods ranging from 1 hr to 24 hr with little or no information on ventilation rates as well as traffic density, traffic mix, road grade and so on. As a result of these deficiencies in the studies which had been made, it was concluded that a computer model should be developed which would predict concentration levels of any exhaust impurity at any point in a tunnel.

The quantity of each component emitted from a particular vehicle at a specific time is dependent upon a number of factors:

1. Type of engine (gasoline, diesel, etc)
2. Size of engine (displacement, horsepower)
3. Condition of engine
4. Type of fuel (octane rating, additives)
5. Adjustment of carburetor
6. Driving mode - acceleration
   - cruising
   - idling
   - deceleration
7. Velocity
8. Rate of acceleration
9. Road grade
10. Elevation above sea level
11. Ambient temperature and relative humidity
12. Vehicle load
13. Condition of control devices such as PCV valve and gasoline tank vapor suppressors.

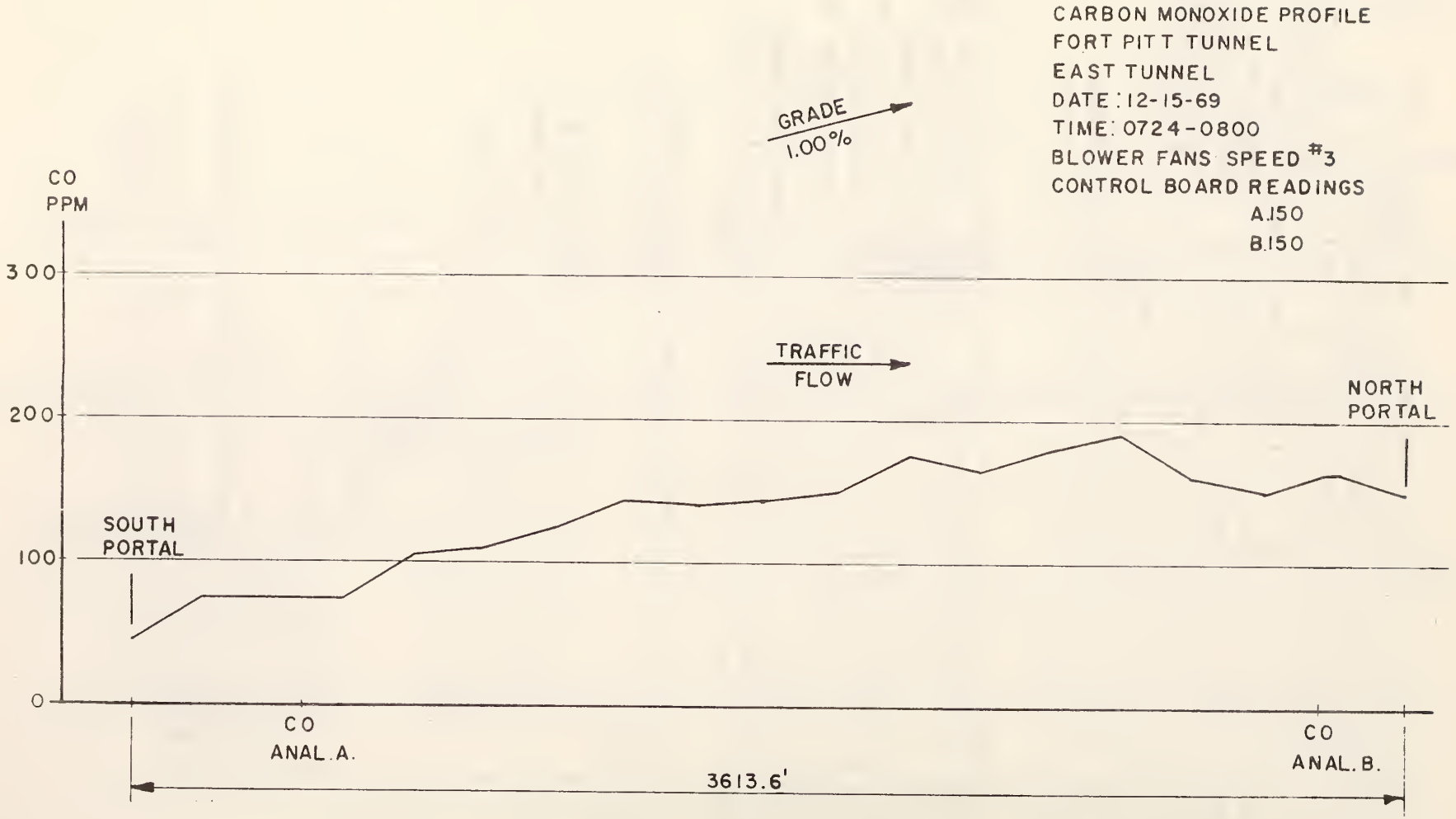


FIGURE 9 - CARBON MONOXIDE PROFILE - FORT PITT TUNNEL
EAST TUNNEL

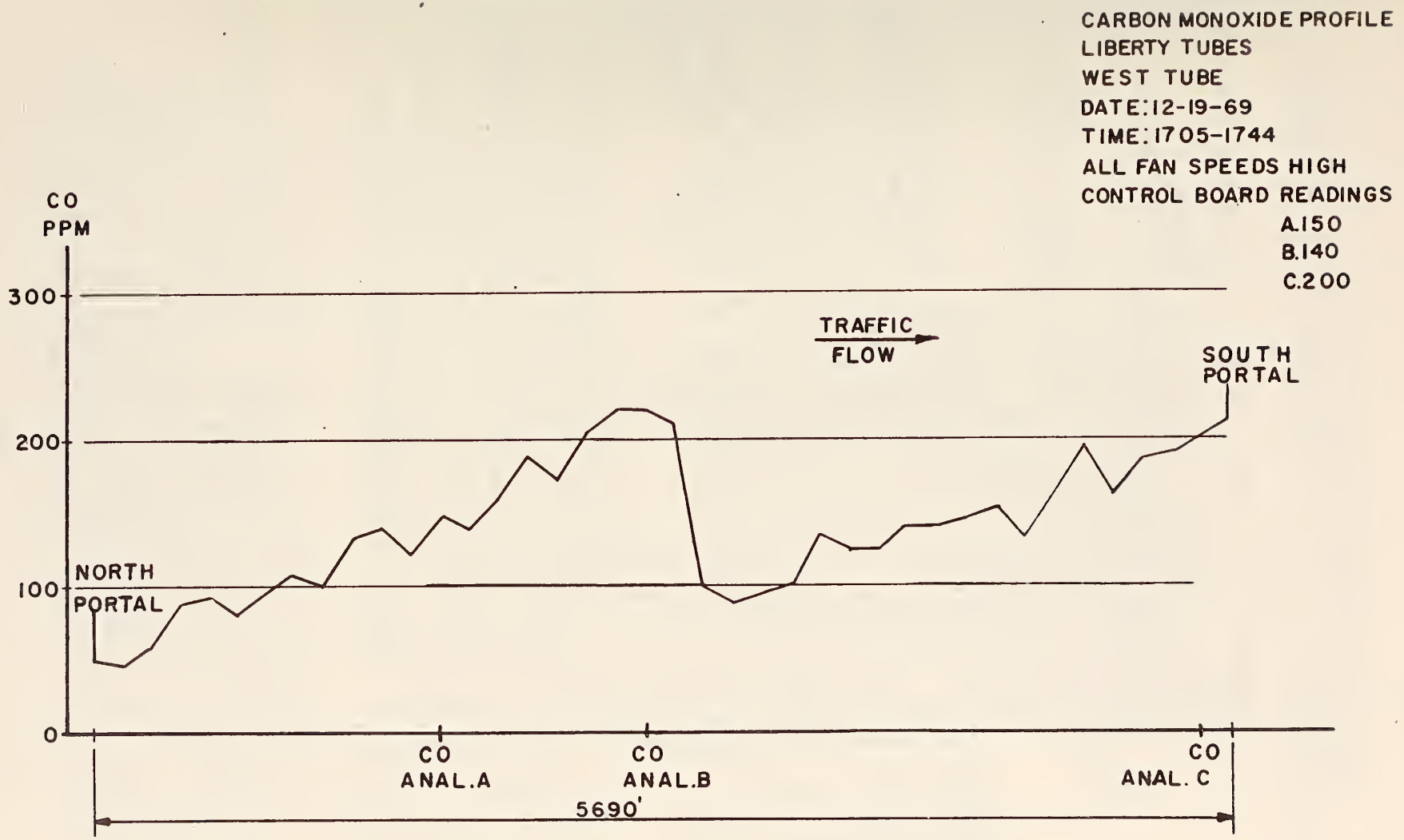


FIGURE 10 - CARBON MONOXIDE PROFILE - LIBERTY TUBES
WEST TUBE

When considering the total pollution generated within a given tunnel, the following additional parameters must be considered:

1. Vehicle mix - cars, diesel trucks, busses, etc.
2. Vehicle density - related to headway or distance between vehicles at various speeds and under various conditions.
3. Ventilation air flow rates.
4. Natural ventilation due to winds at portals, pressure differences at the portals, temperature effects, and the piston effect of the moving traffic stream.

During the early part of the program an evaluation of each of these factors and parameters was initiated with the ultimate goal in mind of establishing a mathematical model representing any tunnel. Such a model would then enable calculation of pollution levels expected in any existing tunnel or proposed tunnel and thereby serve as the basis both for determining pollutant removal system requirements and for the establishment of pollution monitoring system specifications. A preliminary summary of the study of the conditions affecting exhaust emission is given below followed by the description of a computer program for calculating pollution concentration.

Although the exhaust constituents of gasoline engines are similar to those of diesel engines, the relative proportions of these constituents differ considerably. In a gasoline powered automobile, for example, the quantity of carbon monoxide emitted during acceleration may be 6 ft^3/min whereas a diesel bus may emit only 0.2 ft^3 of CO per min.[12] However, the hydrocarbon emission of the same diesel bus engine may be seven times the volume of that emitted by the gas powered automobile. Table 7 outlines the relative emissions of four exhaust constituents under four modes of vehicle operation, namely acceleration, cruise, idle and deceleration.[12]

An important factor in exhaust emission rates aside from the engine is the carburetor. This is particularly so with larger vehicles as illustrated in Table 8 which compares CO emission of cars and trucks as a function of carburetor adjustment.[13] Another exhaust factor is crankcase ventilation. The control device introduced in 1963 reduces pollution rates considerably when it is in proper condition. The concentrations of other exhaust pollutants - nitric oxide and hydrocarbons as well as CO - are influenced by the fuel/air ratio delivered to the engine as shown in Figure 11.[14]

TABLE 7 - EXHAUST GAS EMISSION RATES (ft^3/min)

		Mode			
		Acceleration	Cruise	Idle	Deceleration
Gas auto	CO	6.000	0.700	0.400	0.400
Diesel bus		0.200	0.080	0.025	0.040
Gas auto	NO_x	0.050	0.020	<0.001	<0.001
Diesel bus		0.400	0.083	0.007	0.009
Gas auto	HC	0.016	0.006	0.005	0.024
Diesel bus		0.100	0.030	0.045	0.100
Gas auto	R-COH	0.002	<0.001	<0.001	0.001
Diesel bus		0.008	0.003	0.001	0.009

TABLE 8 - CARBON MONOXIDE PRODUCTION AS A FUNCTION OF CARBURETOR ADJUSTMENT
(Cubic Feet CO per Foot of Travel)

Adjustment of Carburetor	Cars		Trucks	
	18.8 mi/ gallon		9.4 mi/ gallon	5.6 mi/ gallon
Good	0.000248		0.000494	0.000829
Average	0.000646		0.001292	0.002152
Bad	0.001033		0.002066	0.003358

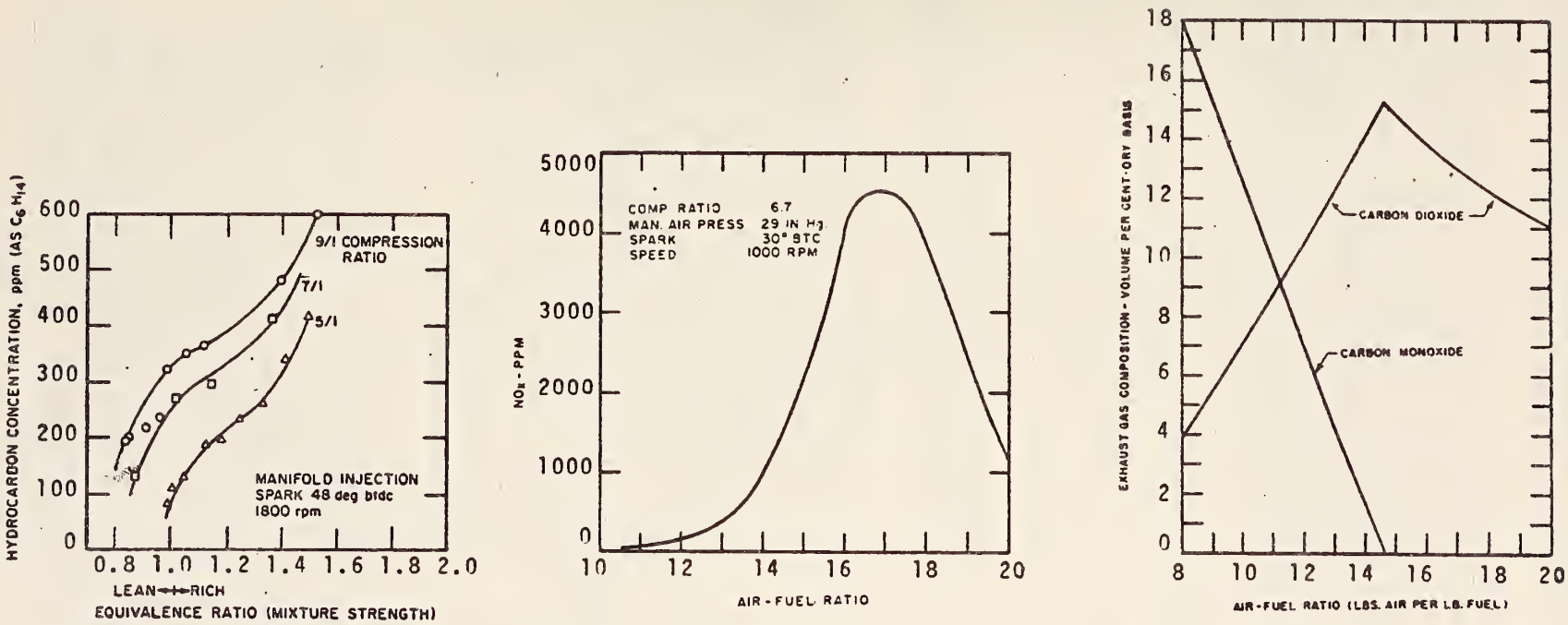


FIGURE 11 - EFFECT OF AIR-FUEL RATIO ON AUTOMOTIVE EXHAUST COMPONENTS

Another factor, particularly in hydrocarbon concentration, is the timing adjustment of the ignition spark.(15)

Exhaust emission rates in units of weight per unit distance traveled for a slow moving vehicle are generally much greater than for one cruising at speeds in excess of 50 miles/hr. Several experimental studies have been reported in the literature which correlate carbon monoxide emission with vehicle velocity and acceleration.(14, 16-19) A summary of some of these results is given in Figure 12. A least-mean squares equation of the combined data was calculated as follows:

$$y = \frac{1.478 \times 10^3}{v} + 10.43 \qquad (2)$$

where v = speed in miles per hour

y = CO emission in gms/veh-mi

25 69.25
30 59.70
35 52.66
40 47.38
45 43.27
50 39.99
55 37.30
60 35.06

Other studies have been reported in which the exhaust emission of pollutants other than CO have been related to vehicle operating mode (velocity, acceleration, etc).

Exhaust emission is also affected by the grade of the road, i.e., inclination of the roadway. The effect of an up-grade on the exhaust emission rate is similar to that of acceleration, that is, it increases the exhaust volume. Conversely, the effect of a down-grade is similar to that of deceleration. The effect of grade on exhaust volume may be stated as a multiplication coefficient applied to the points obtained from Equation 2. The graphs of Figures 13 and 14 give the grade coefficients for CO emission of cars and diesel trucks. For example, Figure 13 shows that a car climbing a 2% grade will emit 1.4 times as much CO as it normally would on a flat (0-grade) roadway while the same car descending a 3% grade will emit only 70% as much CO as it would with zero grade. Coefficients can be similarly established for other exhaust pollutants.(18)

Another exhaust parameter is the elevation above sea level of the roadway. The exhaust emission of an automobile whose carburetor is adjusted for sea level conditions will be considerably greater at higher elevations. An example of this is given in Figure 15 for CO emissions at 5500 feet elevation compared with those at 500 feet.(16) When coupled with the fact that the CO tolerance of the human body decreases as altitude increases, this parameter presents a serious problem in a high altitude tunnel.(20) A few experimental studies of the altitude effect have been reported, primarily those made in connection with a proposed tunnel near Denver which will be located at an elevation of about 11,000 feet above sea level.(21)

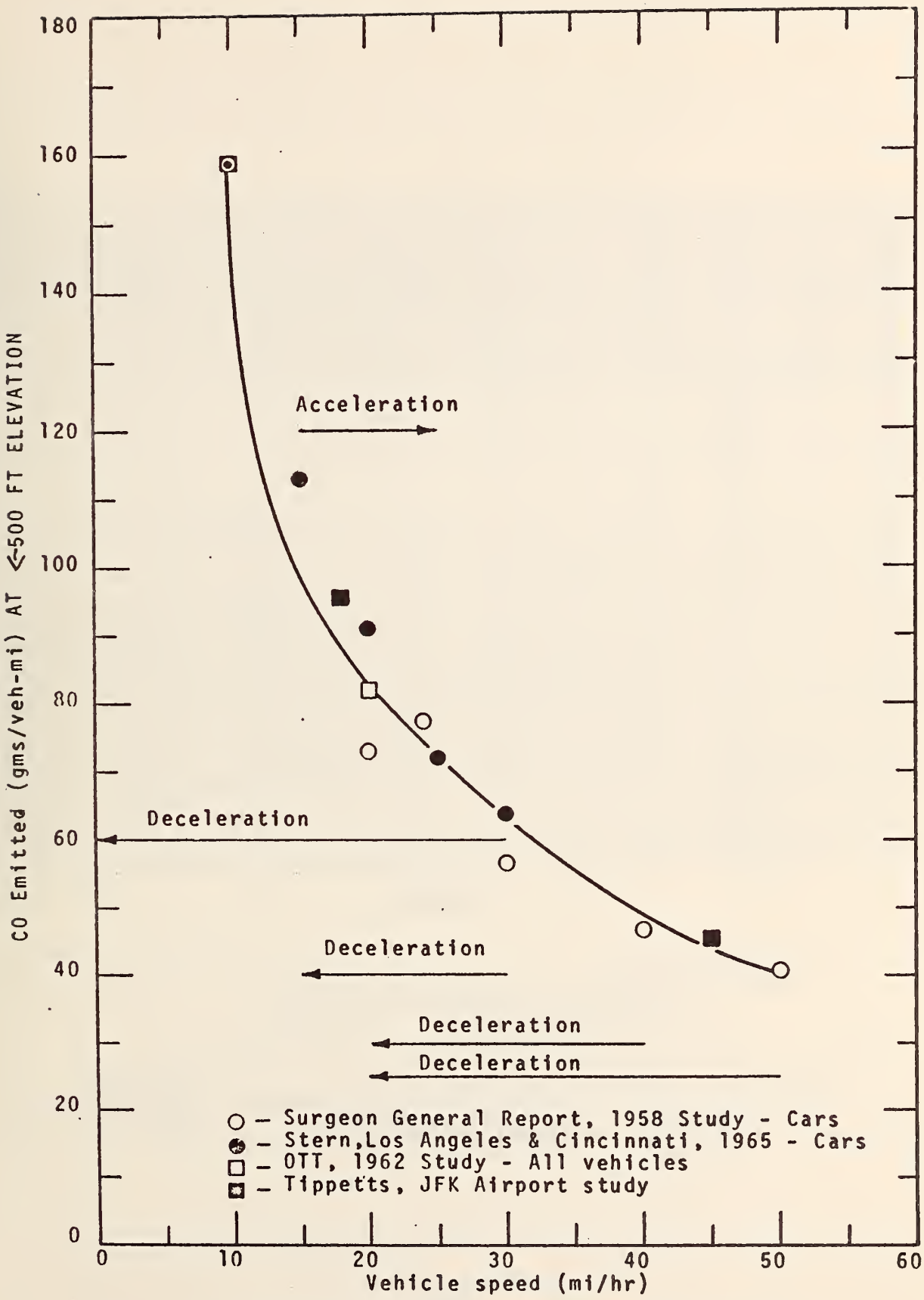
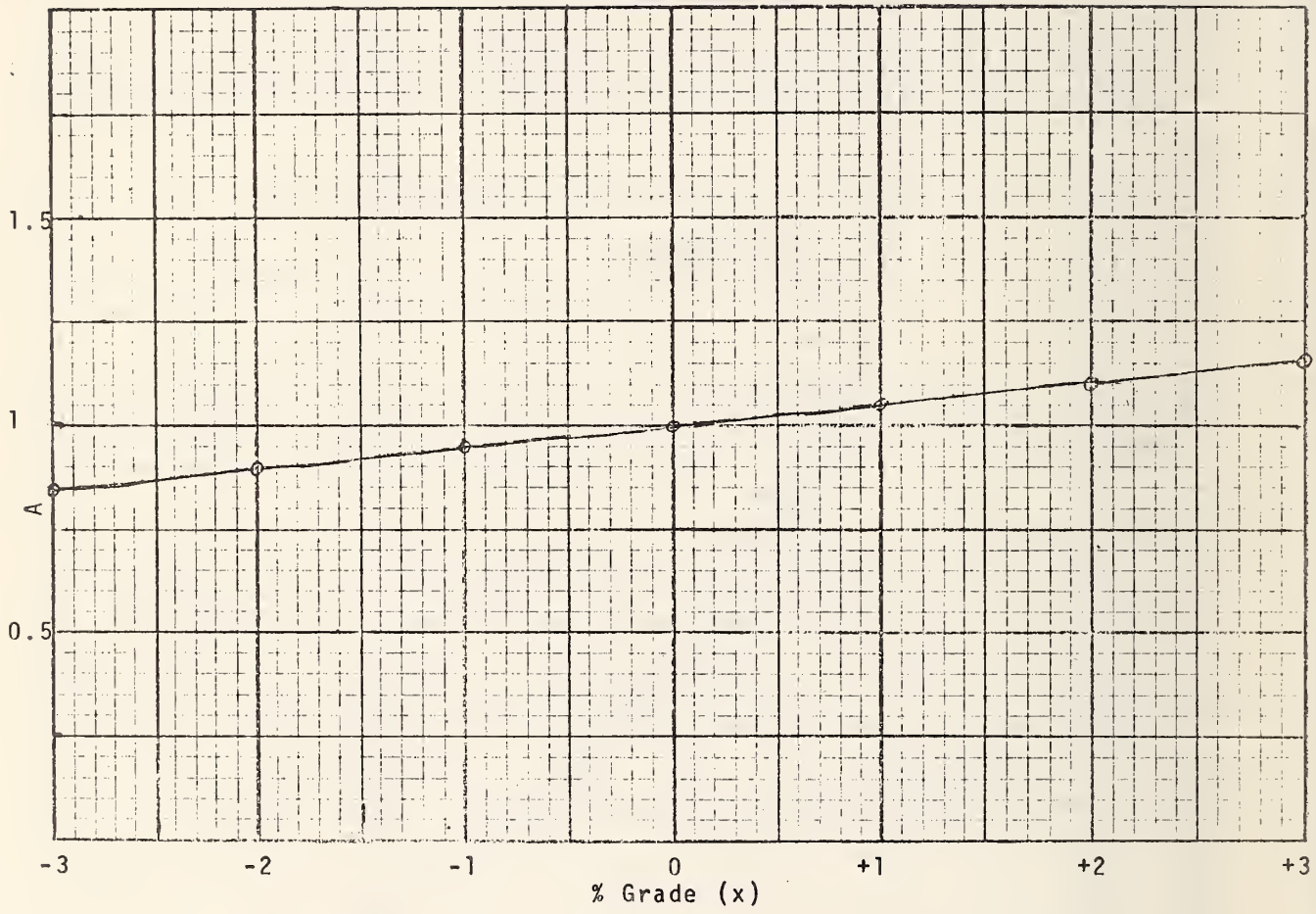


FIGURE 12 - CO OUTPUT VS VEHICLE VELOCITY

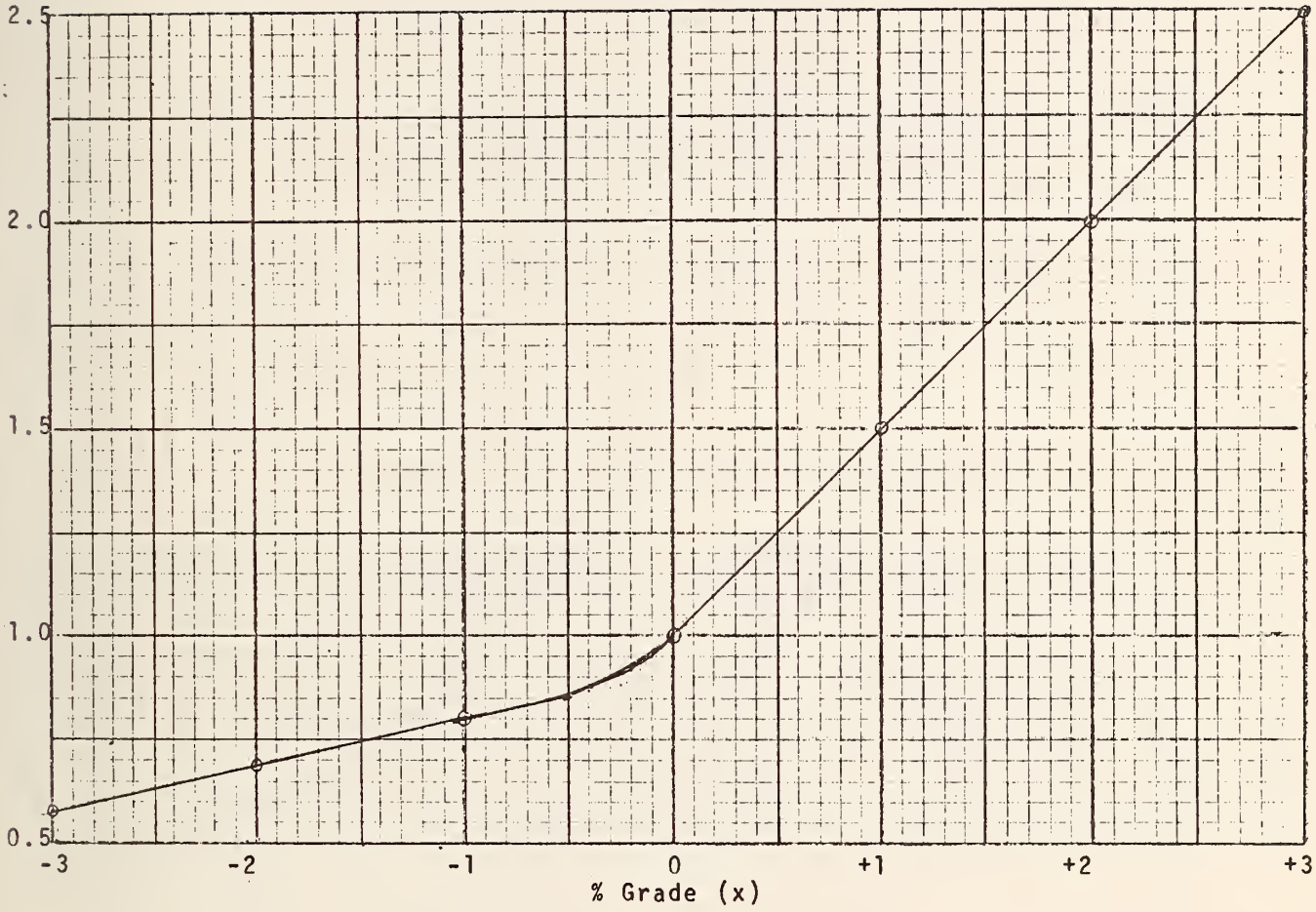


$A = 1.00 + 0.0542\ x$

where x = percent grade

A = CO emission multiplication factor for cars on grade

FIGURE 13 - MULTIPLICATION FACTOR FOR GRADIENT $\left(\begin{matrix}\text{INCREASE}\\ \text{DECREASE}\end{matrix}\right)$ FOR GASOLINE POWERED CARS



B = 1 + x/2 for grades >-0.25%

B = 0.91 + 0.11 x for grades <-0.25%

where x = percent grade
B = CO emission multiplication factor for diesels on grade

FIGURE 14 - MULTIPLICATION FACTOR FOR GRADIENT (INCREASE / DECREASE) FOR DIESELS

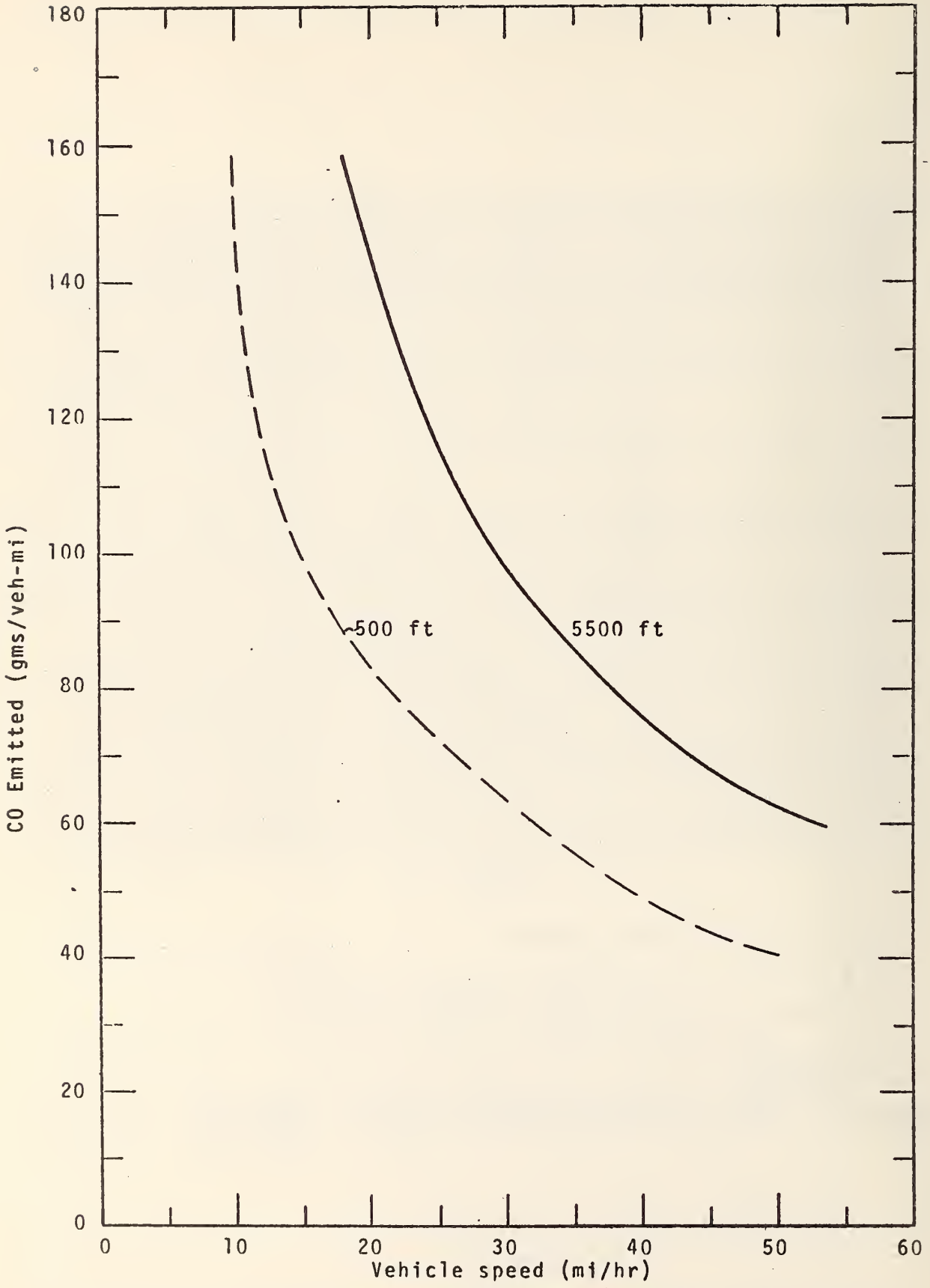


FIGURE 15 - CO EMISSION AT 5500 FT COMPARED WITH THAT AT 500 FT

Available data has been correlated in order to establish an altitude coefficient for our mathematical model. Two regression lines have been computed as follows:

a. CO emission vs altitude with zero grade

$$F = 1.0 + \frac{0.166\ h}{1000} - 0.7035 \times 10^{-8} h^2 \qquad (3)$$

where h = altitude above sea level in feet

F = CO emission multiplication factor for altitude

b. CO emission vs grade at elevations exceeding 7500 ft above sea level

$$y = 92.99 + 28.2x + 6.924x^2 \qquad (4)$$

where x = percent grade

y = CO emission in gms/vehicle-mile.

The computer program which was developed included variables such as emission rates, ventilation rates, vehicle mix, vehicle velocity, road grade, induced ventilation and so on. Other factors such as engine displacement and horsepower, the condition of the engine, age of the vehicle, carburetor adjustment and so on could not be included since these are unknown variables which exist in any traffic mix. This is to say that there is no such thing as an "average car". Development of the computer program was rather straightforward while selection of emission rates proved to be a difficult task in terms of selecting an appropriate emission rate.

The expected concentration level of a gaseous pollutant in a given tunnel may be calculated if the following data are known:

a. Quantity of pollutant generated (cfm/vehicle)
b. Traffic load (vehicles/hr)
c. Fan air flowrate (cfm/mile)
d. Traffic speed (miles/hr)
e. Ambient air pollutant concentration (ppm)

The <u>average</u> pollutant concentration within the tunnel (f) is then calculated by the equation:

$$f(ppm) = \frac{axbx10^6}{cxd} + e \qquad (5)$$

In order to calculate a more definitive profile of a given pollutant through the length of the tunnel, the following elementary model was derived. The assumptions made in the derivation are minimal hence the chief possible source of error is the accuracy of the input data. The assumptions made are:

a. There is no appreciable removal of oxygen nor production of CO_2, or water vapor.
b. The gas composition at a given tunnel point has constant access to the tunnel cross section.
c. Longitudinal diffusion is low.

Assumption a is implied by the mass volume balance for air flow. It states, essentially, that the net gain or removal (of these substances) is small when compared with the quantity of ventilating air passing through the tunnel. The combustion process is

$$\frac{3N + 2}{2} O_2 + H_2(CH_2)_N \longrightarrow NCO_2 + (N + 1)H_2O \quad (6)$$

where the second term represents the saturated hydrocarbon. This process does produce a slight increase in air volume.

The second assumption (uniform composition at a given cross section) is based on turbulence induced by traffic. Since the axial air velocity differs from the vehicle velocity, a turbulent swirl is produced behind each vehicle which tends to homogenize the tunnel air. Also the inlet and outlet air flow patterns minimize the possibility of stagnant air pockets. In the third assumption the pure axial diffusion is extremely low. The axial diffusion caused by the swirls in the wake of the vehicles is larger. However for long tunnels it is small when compared with the axial transport of pollutants.

If these assumptions are applied, the differential equations for pollutant concentration become simple air and pollutant mass balances. The differential equation for air is

$$\frac{dQ}{dl} = V_i - V_o \quad (7)$$

where Q = quantity of air flow in axial direction

l = length

V_i, V_o = cross flow in and out (quantity per unit length).

The differential equation for pollutant is

$$\frac{d(QC)}{dl} = V_i C_i - V_o C + G \qquad (8)$$

where C = pollutant concentration

C_i = ambient pollution concentration

G = pollution generated per unit length of tunnel.

The above equations are subject to the boundary conditions:

$$Q(0) = Q_o \qquad (9)$$

and

$$C(0) = C_{in} \qquad (10)$$

where Q_o = inlet axial flow

C_{in} = pollution concentration at tunnel inlet.

The above equations can best be cast in a "finite difference" form. Several forms are available of which the following are the simplest:

$$Q^{(n)} = Q(n-1) + (V_i(n) - V_o(n))dl \qquad (11)$$

$$C(n) = V_i(n)C_i dl + Q(n-1)C(n-1) + G(n) \qquad (12)$$

where V_i, V_o and G are evaluated at the mid point between (n-1) and (n). These equations require that Q be always positive and are always stable.

The computer program solves the above set of equations stepwise from tunnel entrance to tunnel exit. The step length (dl) may be selected as desired. The program is written so as to check the direction of axial air flow at each step and will stop if Q becomes negative. For tunnels in which air flow direction in some segments is opposite that in other segments, the program would be applied to the individual tunnel segments so as to keep Q positive. Since the exit air flow is given the tunnels or tunnel segments may be conveniently linked.

A print out of the program is presented on page 36. The program is normally read from magnetic tape, however a punched tape recording of the program has also been prepared and will be forwarded with this report. A glossary of input and readout data is given on page 37. This lists the units and encoding symbols used for each of the variables used in the program.

```
 L
C P IS CU FT/VEH MILE; QTI/O IS CFM/MILE;VI IS CFM
C TUNNEL LENGTH AND DELT IS MILES;VEH IS VEH/HR;CONC ARE PPM
 DIMENSION QTI(5),QTO(5)
24 TYPE 1
1 FORMAT (/,/,/,"TUNNEL CONC",/,"POL. COEFS")
 ACCEPT 2, P1,P2
2 FORMAT (E)
 TYPE 3
3 FORMAT (/,"TRANS AIR IN",/,"TRANS AIR OUT")
 ACCEPT 2,QTI(1),QTI(2),QTI(3),QTI(4),QTI(5)
 ACCEPT 2,QTO(1),QTO(2),QTO(3),QTO(4),QTO(5)
6 TYPE 4
4 FORMAT (/,"END AIR IN TUNNEL LENGTH  TUNNEL DELT L")
  ACCEPT 2,VI,BL,DL
 IF (VI) 6,7,7
7 TYPE 27
27 FORMAT (/,"VEHICLES/HR; INLET, AMBIENT CONC")
 ACCEPT 2,VEH1,VEH2,CI,CO
 TYPE 32
32 FORMAT (/,"CONT")
 ACCEPT 2,CONT
 IF (CONT) 33,34,34
33 W=0.0
 QDIS=0.0
34 TYPE 5
5 FORMAT (/,/,"TUNNEL POS          CONC")
 AL=0.0
        ISWT=1
35      IF (AL+DL-BL) 8,8,36
36      DL=BL-AL
        ISWT=-ISWT
8 AL=AL+DL/2.0
13 QTIC=(((QTI(5)*AL+QTI(4))*AL+QTI(3))*AL+QTI(2))*AL+QTI(1)
 IF (QTIC) 15,16,16
15 TYPE 17,QTIC
17 FORMAT (/,"TRANS IN IS NEG",E)
 GO TO 25
16 QTOC=(((QTO(5)*AL+QTO(4))*AL+QTO(3))*AL+QTO(2))*AL+QTO(1)
 IF (QTOC) 18,19,19
18 TYPE 20,QTOC
20 FORMAT (/,"TRANS OUT IS NEG",E)
 GO TO 25
19 VO=VI+DL*(QTIC-QTOC)
 IF (VO) 21,22,22
21 TYPE 23
23 FORMAT (/," AIR VEL ZERO")
 AL=AL+VO/(QTOC-QTIC)+0.5*DL
 GO TO 25
22 CI=VI*CI+QTIC*DL*CO+(VEH1*P1+VEH2*P2)*1.6667E4*DL
 CI=CI/(VO+QTOC*DL)
 AL=AL+DL/2.0
 VI=VO
 TYPE 28,AL,CI
28 FORMAT (/,E,E)
        QDIS=QDIS+QTOC*DL
        W=W+QTOC*DL*CI
 IF (ISWT) 31,31,35
31 TYPE 30,VO
30 FORMAT (/,"DISCHARGE FLOW",E)
        IF(QDIS) 38,24,38
38      CI=W/QDIS
        TYPE 37,CI
37 FORMAT (/,"AVG CONC",E)
 GO TO 24
25 TYPE 26,AL
26 FORMAT (/,"POSITON",E)
 GO TO 24
 END
```

TYPICAL PRINT OUT OF COMPUTER PROGRAM

GLOSSARY OF SYMBOLS FOR COMPUTER PROGRAM

INPUT DATA:

SYMBOL	VARIABLE	UNITS
P	pollution emitted	cubic feet per vehicle mile
QTI	air cross flow into tunnel	cubic feet per minute per mile
QTO	air cross flow out of tunnel	cubic feet per minute per mile
VI	axial air flow into tunnel	cubic feet per minute
BL	tunnel length	miles
DL	incremental length	miles
VEH	traffic flow	vehicles per hour
CONC.	pollutant concentration	parts per million (by volume)

-1 = new start +1 = continue summing for duct emission

OUTPUT DATA:

tunnel position	miles
concentration of pollutant	ppm (vol)
exhaust air flow	CFM
average exhaust duct concentration	ppm (vol)

An actual data computation is presented on page 39. Output data consists of columns showing concentration levels for a given pollutant at incremental distances along various sections of the tunnel. Section boundaries are usually determined by blower shaft locations and changes in road grade level (or percent inclination). The exhaust air flow from the section is given below the concentration/location columns followed by the average concentration of the given pollutant in the exit air duct (where applicable).

Emission Rates for CO, H-C, NO_x and Particulates - As stated before, selecting appropriate emission rates proved to be a difficult and frustrating task. The XIII World Congress on Road Tunnels[12] showed that a great discrepancy existed in regard to emission rates. Some of the data reported in this reference dated back to 1919, and it was found later that in some cases this data is still being used to predict emission rates. Table 7 shows the emission rates of CO, NO_x, HC and R-COH from gasoline and diesel engines as a function of mode of operation as reported in 1965. This same reference also reports emission rates of CO as a function of carburetor adjustment for cars and trucks (Table 8).

Table 9 lists the emission rates for CO as summarized in XIII World Congress on Road Tunnels.[22] This table represents the best data available in 1957 and is composed primarily of results reported by the Coordinating Research Council.[23]

The Surgeon General's Report of 1962[24] lists the emission rates for late 1950 automobiles. Table 10 lists the results; values for H-C and NO_x are shown in this table also and will be discussed later.

Over the past few years, the emission rate of CO from gasoline powered vehicles has been decreasing. Table 11 shows the emission rates for pre-1966, 1966-1969 and 1970 passenger cars and light trucks as well as heavy duty trucks.[25,26]

Stormont[27] reports emission rates of 65 g CO/veh-mi for 1965-1967 models, 35 gm CO/veh-mi for 1968 models, 25 gm CO/veh-mi for 1969 and 1970 models. A target of 4.7 gm CO/veh-mi is set for 1975 models.

Federal Regulations for CO emissions as reported in Environmental Science and Technology[28] are:

Year	gm CO/veh-mi
1968	35.1
1970	23.0
1972	39.0
1975	4.7

```
          0.7209 0.3341

TRANS AIR IN
TRANS AIR OUT 0.4684E6 0 0 0 0
0.264E6 0 0 0 0

END AIR IN TUNNEL LENGTH  TUNNEL DELT L26600 0.235 0.02

VEHICLES/HR; INLET, AMBIENT CONC 1180 352 0 0

CONT-1


TUNNEL POS           CONC
 0.200000E-1      0.850087E+1
 0.400000E-1      0.142816E+2
 0.599999E-1      0.183770E+2
 0.800000E-1      0.213752E+2
 0.999999E-1      0.236307E+2
 0.119999E+0      0.253666E+2
 0.139999E+0      0.267287E+2
 0.159999E+0      0.278155E+2
 0.179999E+0      0.286954E+2
 0.199999E+0      0.294170E+2
 0.219999E+0      0.300154E+2
 0.235000E+0      0.304023E+2
DISCHARGE FLOW 0.766339E+5
AVG CONC 0.235749E+2


TUNNEL CONC
POL. COEFS 0.9876 0.86

TRANS AIR IN
TRANS AIR OUT0.6011E6 0 0 0 0
0.6266E6 0 0 0 0

END AIR IN TUNNEL LENGTH  TUNNEL DELT L 0.76634E5 0.4868 0.05

VEHICLES/HR; INLET, AMBIENT CONC 1180 352 30.4 0

CONT-1


TUNNEL POS           CONC
 0.500000E-1      0.333033E+2
 0.100000E+0      0.354140E+2
 0.150000E+0      0.369414E+2
 0.200000E+0      0.380414E+2
 0.250000E+0      0.388298E+2
 0.300000E+0      0.393920E+2
 0.350000E+0      0.397909E+2
 0.399999E+0      0.400723E+2
 0.449999E+0      0.402698E+2
 0.486800E+0      0.403804E+2
DISCHARGE FLOW 0.642205E+5
AVG CONC 0.381655E+2


TUNNEL CONC
POL. COEFS 1.1944 2.7607

TRANS AIR IN
TRANS AIR OUT 0.8786E6 0 0 0 0
0.676E6 0 0 0 0

END AIR IN TUNNEL LENGTH  TUNNEL DELT L 0.642205E5 0.4621 0.05

VEHICLES/HR; INLET, AMBIENT CONC 1180 352 40.38 0

CONT-1
```

Section N4
40 ppm
CO Monitor Chart Reading

Section N3
50 ppm
CO Monitor Chart Reading

PORTION OF COMPUTER PRINTOUT
FOR LINCOLN TUNNEL-WESTBOUND TUBE

TABLE 9 - CO EMISSIONS REPORTED IN REFERENCE 22
Emission Rate gm CO/veh-mi

Speed (mph)	Downgrade	Level	Acceleration	Upgrade
40	38	51	175	73
35	41	56	195	86
30	45	64	225	99
25	40	70	269	112
20	56	78	311	128
15	74	99	410	159
10	106	128	573	214

TABLE 10 - GRAMS OF POLLUTANT EMITTED PER MILE FOR FIXED MODE OF OPERATION
(gm/veh-mi)

Mode	CO	Gross HC	NO_x
Cruise:			
20 miles per hour	72	9.1	----
30 miles per hour	57	6.4	2.7
40 miles per hour	47	5.4	----
50 miles per hour	40	7.7	5.2
Acceleration:			
0 to 60 miles per hour	381	28	----
0 to 25 miles per hour	240	29	----
15 to 30 miles per hour	120	14	10.2
Deceleration:			
50 to 20 miles per hour	26	6.8	----
30 to 15 miles per hour	40	5.9	----
30 to 0 miles per hour	60	7.7	----
40 to 20 miles per hour	30	5.0	----

TABLE 11 - CARBON MONOXIDE EMISSION, gm CO/VEHICLE-MI

Average Speed mph	Passenger Cars & Light Trucks			Heavy Duty Trucks (no emission controls)		
	Pre-1966	1966-69	1970	6,000-10,000 GVW	10,000-20,000 GVW	20,000# GVW
15	111	45	29	211	275	310
20	87	36	23	166	216	244
35	54	22	14	103	133	151
55	37	15	10	70	91	103

This applies only to light duty vehicles.

Many other references were reviewed and are included in the Bibliography section of this report. For the current mixture of model years we have selected an average CO emission rate from gasoline powered vehicles of 40 gm CO/veh-mi. If the Federal Standards are met and as older models are phased out of operation, this value will decrease.

Less information was found on CO emission from diesel powered vehicles, and again some of this information was contradictory. For example, all references on CO emission from diesel engines listed some positive values, whereas the Surgeon General's Report of 1962[24] listed an emission rate of zero for CO. Rispler [12] reported a CO emission rate for diesel engines at 40 mph cruise of 4.3 gm/veh-mi. Rose[29] reported an emission rate of CO from diesels of about 3.5 gm/veh-mi under cruise conditions. From this limited data, we conclude that under cruise conditions, the CO emission rate from diesels is ∿4 gm/veh-mi. Emission rates of CO from diesels for the effects of road grade can be adjusted using the data in Figure 14.

Hydrocarbon emissions have been studied by a number of investigators. In the case of hydrocarbons, emissions are much more dependent upon the condition of the car and the emission control devices installed on cars than are CO emission rates. The Surgeon General's report[24] listed the emission rates as a function of mode of operation. (Table 10). This same reference reports diesel emission of H-C as 4.5 gm H-C/veh-mi at 30 mph (cruise), 20.5 gm H-C/veh-mil under acceleration and 17.3 gm H-C/veh-mi under deceleration.

Stormont[27] reports H-C emissions according to the year of the automobile under cruise conditions. The values are:

Year	gm H-C/veh-mi
1965-1967	12
1970	6
1972	2
1975	0.5 (Projected)

The Federal Standards[28, 30] for H-C emissions from passenger vehicles are as follows:

Year	gm H-C/veh mi
1972-1974	3.4
1975	0.46

These values apply to light duty vehicles only.

In 1965, Rose[29] reported H-C emission for gasoline and diesel engines under cruise conditions as 5.8 gm H-C/veh-mil and 6.2 gm H-C/veh mi, respectively.

On the basis of the data which were compiled on H-C emissions, we selected an average emission rate of 2.7 gm H-C/veh-mi for gasoline powered vehicles and 3.4 gm H-C/veh-mi for diesels. Hydrocarbon emission by diesels are about 8.0 gms/veh-mi under accelerating conditions and 10.5 gm/veh-mi under decelerating conditions.

The emission of oxides of nitrogen from motor vehicles exhaust is generally reported in terms of NO_x, i.e., the total of NO plus NO_2. Studies have shown that approximately 80% of the NO_x emitted is in the form of NO. In tunnels, where the residence time of the exhaust gases is of the order of seconds, there is little time for NO to convert to NO_2, hence approximately 80% of the NO_x in tunnels is there as NO.

The Surgeon General's Report lists NO_x emissions of 2.6 gm NO_x/veh-mi at 30 mph and 5.2 gm NO_x/veh-mi at 50 mph cruise. The same reports lists the emission from diesels as 8.9 gm NO_x/veh-mi and 8.8 gm NO_x/veh-mi under acceleration.

Stormont reported NO_x emissions according to the vehicle year:

Year	Emission Rate (gm NO_x/veh-mi)
1960	6
1965-1971	5
1972	4
1973	3
1975	1

The values listed for 1972-1975 are projected values.

Rose reported an emission rate of 3.9 gm NO_x/veh-mi for gasoline engines in the cruise mode. Diesels in a cruise mode emitted 10.0 gm NO_x/veh-mi.

Although the data are limited with respect to NO_x emission, the reported values are in relatively good agreement. We have selected an emission rate of 4.0 gm NO/veh-mi for gasoline engines and 8.0 gm NO/veh-mi for diesel engines. It must be recognized that various driving modes will change these emission rates, but the data on NO_x emissions as a function of driving mode is limited.

The data on particulates are even more limited than for other exhaust contaminants. Frey and Corn[31] studied the particle size and concentration in vehicle exhaust gases. The particle size ranged from 0.01 to 5 u. Gasoline engines were reported to emit 0.4 gm/veh-mi while diesel engines emitted 5.0 gm/veh-mi. The Environmental Protection Agency[32] has set standards for particulate emissions for 1975 model cars - 0.1 gm/veh-mi.

In summary, it has been difficult to select standard emission rates for gasoline and diesel powered vehicles under various driving modes, with the possible exception of CO. However, by limiting the selection of emission rates reported during the 1960's only, we believe the selected rates are representative of the gasoline and diesel powered vehicle mix which is currently on the road. The emission rates which we have selected are as follows:

Type of Vehicle	Mode of Operation	Emission Rates (gm/veh-mi) CO	HC	NO_x	Particulates
Gasoline	Cruise*	40	2.7	4.0	0.4
Diesel	Cruise	4.0	3.4	8.0	5.0
Gasoline	Projected 1970	23	2.2	---	---
Gasoline	Projected 1975**	4.7	0.5	0.9	0.1

*Emission rates for CO can be corrected for grade by using factors given in Figures 13 and 14.
**Federal Standards

Verification of Computer Model - After selection of what was felt to be typical emission rates from gasoline and diesel vehicles, it was decided that an in-field survey of tunnels would be made in order to compare the actual contaminant concentrations with the computer predicted concentrations. Measurements were made at the following tunnels:

1. Baltimore Harbor Tunnel
2. Allegheny Mountain Tunnel
3. Lincoln Tunnel
4. Fort Pitt Tunnel
5. Armstrong Tunnel

In most cases, the CO levels of the tunnel were taken from the continuous monitoring data while in one case CO, H-C, NO and/or particulates were measured.

The Baltimore Harbor Tunnel is a 6700 ft long dual tube tunnel which is part of an expressway circling the city of Baltimore. The Harbor Tunnel is located beneath the Patapsco River. The northern portal and ventilation building are surrounded by industrial plants while the southern one lies in rather open country. Tolls are collected at booths located about 0.7 miles from the south portal. Each tube is staffed by 3 or 4 patrolmen on a continuous basis with a shift change every two hours. Each tunnel patrolman spends a total of 4 hours per day inside the tunnel - most of the time in semi-enclosed shelter booths. The traffic load varies from 55,000 to 75,000 vehicles per day. Transverse ventilating is used and CO is continuously monitored in the exhaust stacks.

One of the chief reasons for selecting the Harbor Tunnel for our survey was the fact that complete records are maintained which include the following:

- Traffic counts and traffic type, according to number of axles
- Continuous ventilation rate data
- Detailed accounting of all traffic stoppages in the tunnel
- Complete set of engineering drawings
- Ambient weather conditions.

During the visit spot checks were taken of traffic count and mix and vehicle residence time or speed. Particulate samples were also obtained by portable MSA mine samplers placed on the tunnel catwalk. The weight per unit-volume of sample collected was about 0.6 mg/m^3 which is the same concentration as the sample taken at the Fort Pitt Tunnel. The average CO concentration in the tunnel, as recorded by monitors sampling exit air, averaged about 75 ppm over a three day period and rarely exceeded 180 ppm during peak traffic periods.

Traffic counts were made of both gasoline and diesel powered vehicles in the east tube over a period of about 15 mins. The CO traces for this period were then obtained from the Baltimore Harbor Tunnel authorities. Figure 16 shows the road grade of the tunnel and the reported ventilation rates for the period during which traffic counts were made. Figure 17 is an actual trace of the CO monitors in the tunnel during the period when traffic counts were made. The inputs to the computer program included:

1. Ventilation pattern and flow rates, road gradient and tunnel section lengths are shown in Figure 16.
2. Traffic count and mix: 1260 gas/hr
   268 diesel/hr

1568

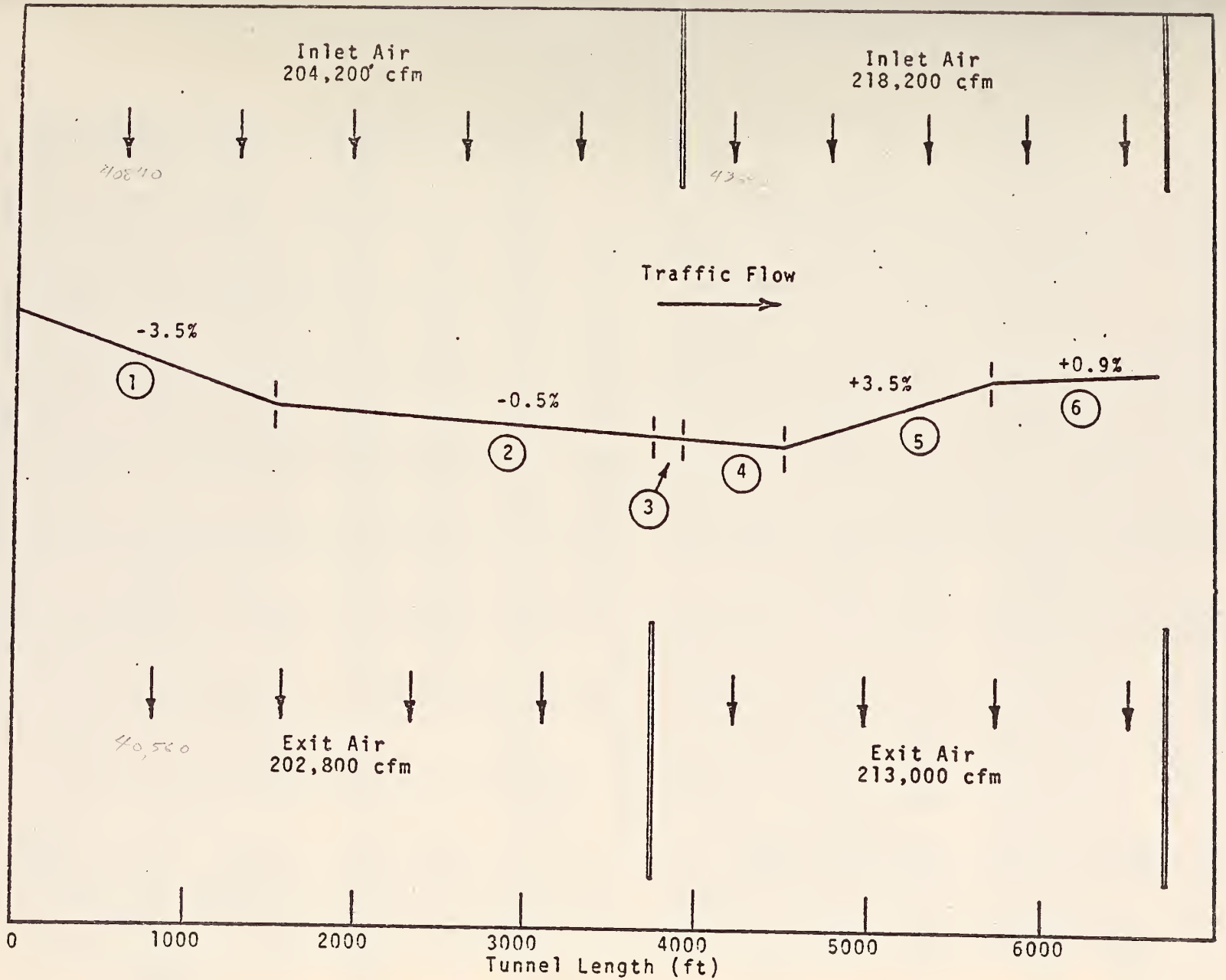


FIGURE 16 - VENTILATION RATES AND ROADWAY GRADIENT FOR BALTIMORE HARBOR-EAST TUBE

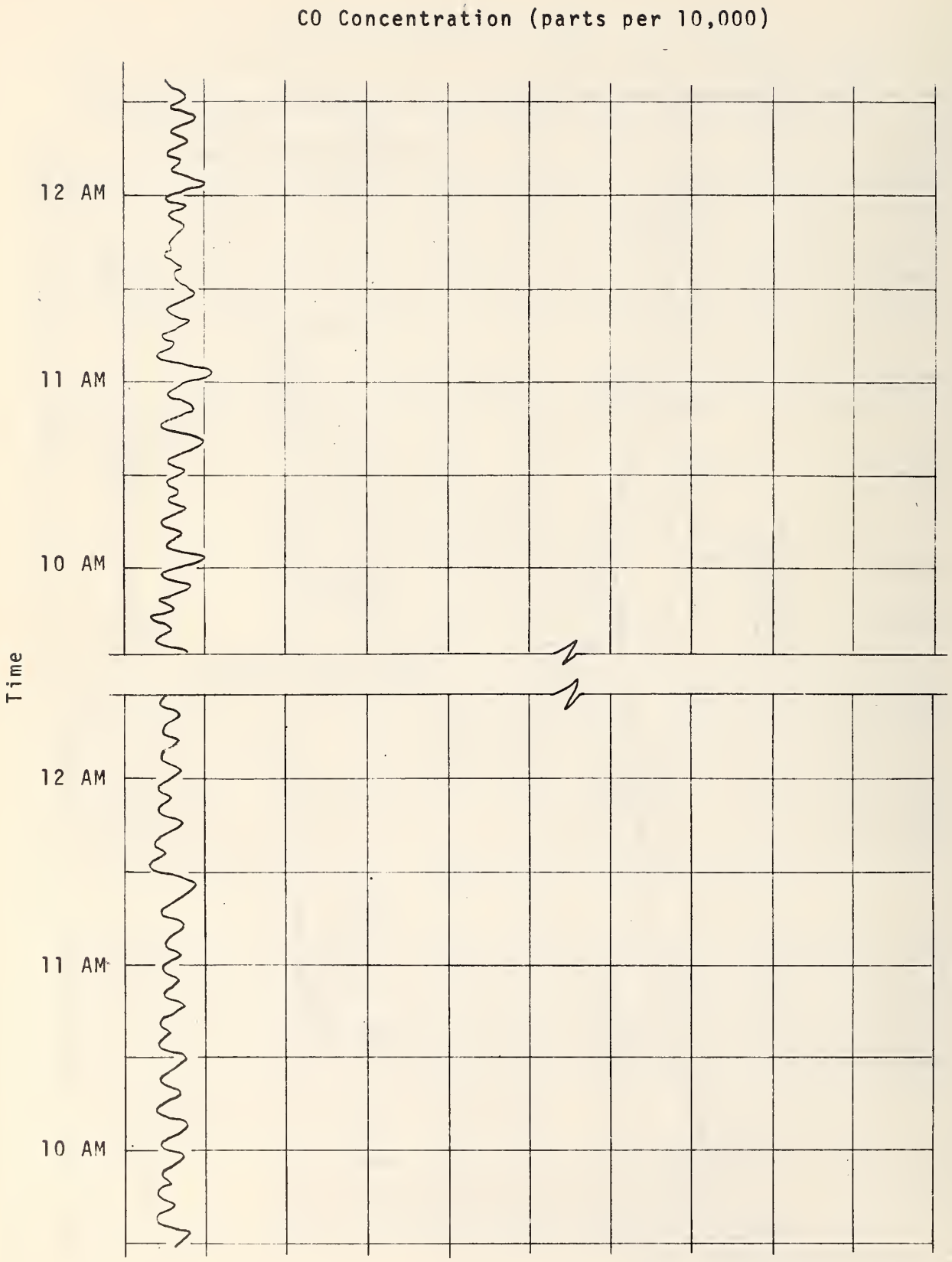


FIGURE 17 - ACTUAL TRACE OF CO MONITOR READINGS IN THE BALTIMORE HARBOR TUNNEL

3. Vehicle velocity: 42-50 mph
4. Ambient CO level: 2 ppm assumed
5. Piston effect: ∿23% of fan rates (50,000 cfm)
6. Emission rate for CO as a function of the above conditions.

The CO concentration profile calculated by the mathematical model method is presented in Figure 18. The sharply defined maximum and minimum values are similar to the pattern obtained by other investigators. These peaks are caused by the combined effects of ventilation patterns and CO emission rate differentials.

Since the tunnel CO monitor's sampling probes are installed in the exit air ducts instead of at road level, a direct comparison with calculated results at a given point in the tunnel can only be obtained by actual CO measurement at a given point. However, an average CO concentration calculated from the profile values should agree with the CO levels indicated by the permanent tunnel CO monitors. Hence an additional step was added to the computer program which yields average CO concentration values at the end of each tunnel section and a cumulative average value for a series of combined tunnel sections. Average CO concentration values obtained were:

a. 71.1 ppm for Section (1 and 2)
b. 75.9 ppm for Sections (3,4, 5 and 6)

Actual values taken from the recorders in the control room during the time of this test were, respectively:

a. 60 ± 15 ppm (1 and 2)
b. 65 ± 15 ppm (3, 4, 5 and 6).

Figure 19 is a plot of these average results. The results indicate that the computed CO level falls within the measured CO concentration.

The Allegheny Mountain Tunnel is a dual tube tunnel located on the Pennsylvania Turnpike. It differs from all of the other tunnels which we visited in that it is located in a rural area while the others were all urban tunnels. Each tube is 6100 ft long and has an average grade of ± 0.5%. The tunnels are ventilated in a longitudinal distributive fashion. Ventilation is provided by overhead ducts and fans mounted at either portal of each tube. Flowrates may be adjusted in four steps from 450,000 cfm/tube to 1,200,000 cfm/tube. Vitiated air is exhausted through the traffic portals. Anemometer readings of wind velocity inside the duct of the south tube

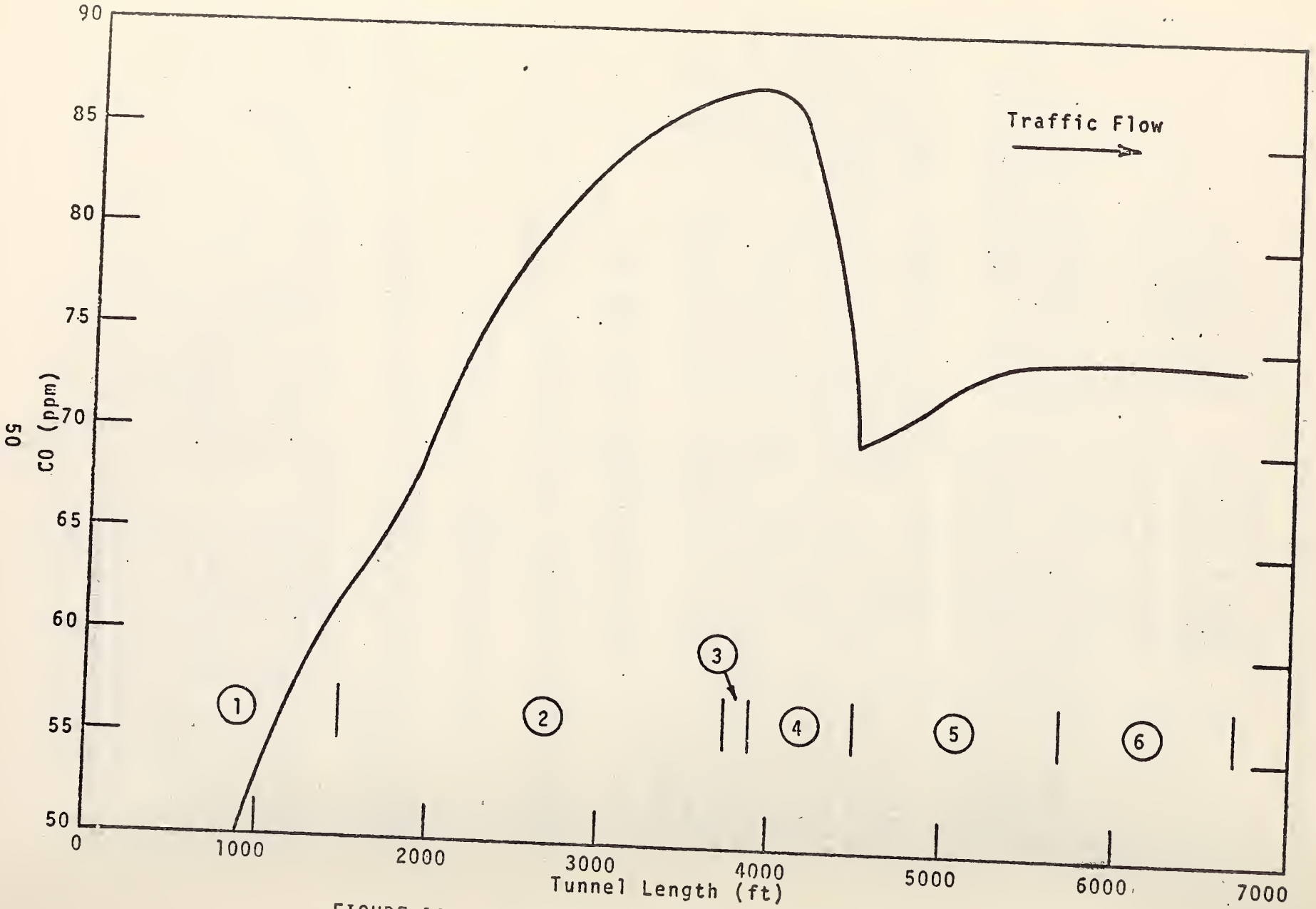


FIGURE 18 - COMPUTER PREDICTED CO PROFILE-BALTIMORE HARBOR TUNNEL-EAST TUBE

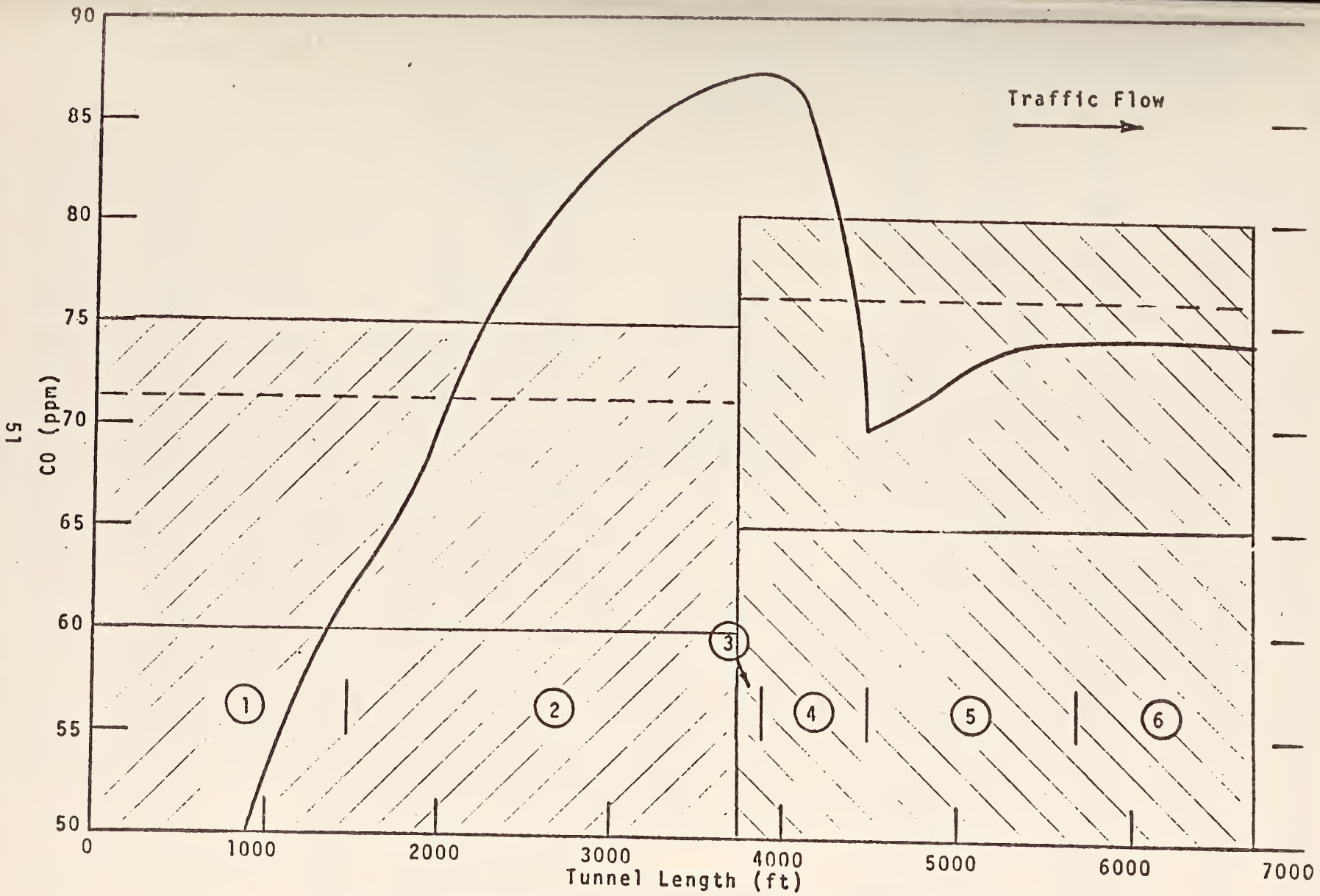


FIGURE 19 - CALCULATED AND ACTUAL CO CONCENTRATION FOR BALTIMORE HARBOR TUNNEL-EAST TUBE

yielded values of 600 ft/min at a point 30 ft from the intake fan and 390 ft/min at duct midpoint.

Traffic and gas/diesel mix was rather constant throughout the day and was nearly identical in both directions:

295 ± 10 gasoline vehicles/hr
105 ± 5 diesel vehicles/hr

Average speed for the vehicles was determined by telephone communications at each portal, and was 55 to 60 mph for cars and 50 mph for large trucks.

Carbon monoxide monitoring instruments are located in the ventilation building control rooms. Air inlet probes are located in three niches in the wall of each tube. The CO levels indicated by the center tunnel monitors are generally higher than those of the other monitors. However, the concentration ranges of all six monitors were below 40 ppm throughout the day of our visit. (Fig. 20)

Input parameters:

Traffic count and mix:	291 gas/hr 110 diesel/hr
Ventilation flow rate:	450,000 cfm/duct (see Fig. 20)
Ambient CO level:	1.0 ppm assumed
Road gradient:	See Fig. 20
Tunnel length:	See Fig. 20

The CO level was quite low and nearly constant throughout the length of the tunnel during the period that the traffic counts were made. Monitors located in niches at three points inside the tunnel each showed CO levels averaging 20 ppm. Since the response accuracy of the monitors is ± 10 ppm the computed result (15 ppm CO) is considered in agreement with actual. If a 20% factor is added for piston effect the calculated average CO concentration drops to 12 ppm which is still in agreement with the monitors.

Other potential conditions for the Allegheny Tunnel were computed (Figure 21). These included:

1. 1000 cars/hr @ 40 mph with 450,000 cfm forced and 50,000 cfm natural and piston ventilation (Curve A).

2. A complete power failure with 1000 cars/hr @ 40 mph with a 180,000 cfm piston effect (Curve B).

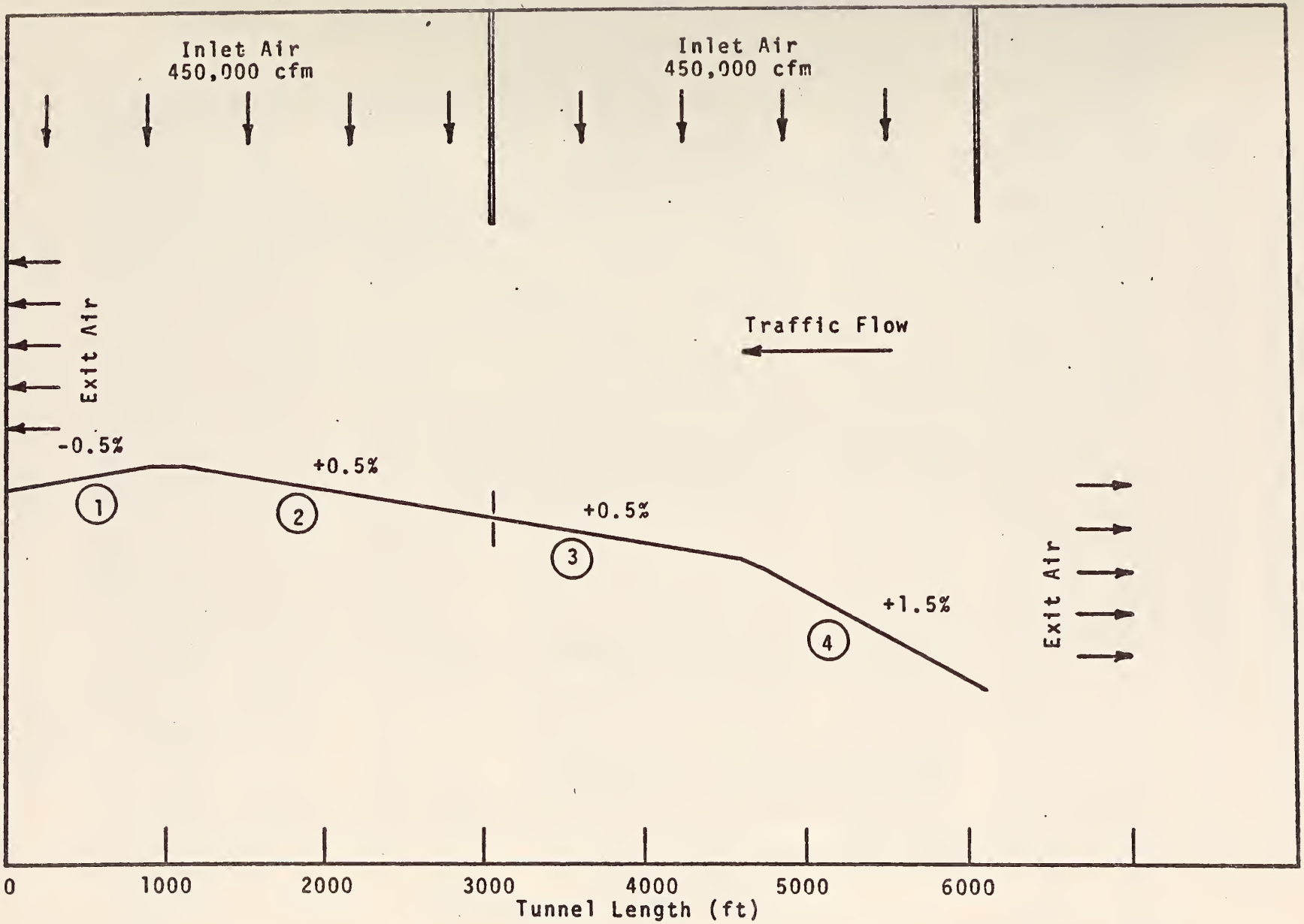


FIGURE 20 - VENTILATION RATES AND ROADWAY GRADIENT FOR ALLEGHENY-NORTH TUBE

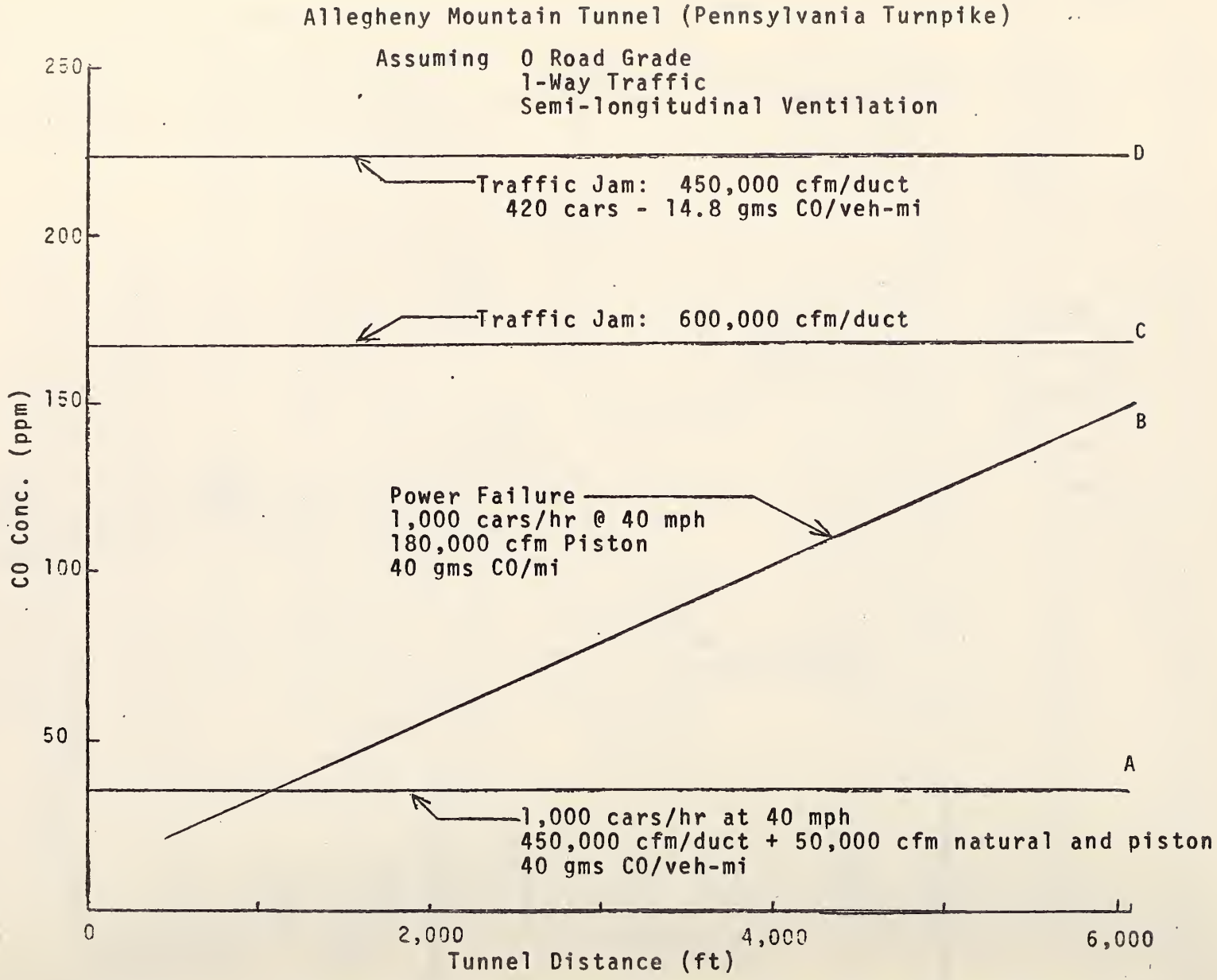


FIGURE 21 - COMPUTED TRAFFIC CONDITIONS FOR ARMSTRONG MOUNTAIN TUNNEL

3. A traffic jam with a forced ventilation rate of 600,000 cfm (Curve C).

4. A traffic jam with a forced ventilation rate of 450,000 cfm (Curve D).

With 1000 cars traveling at 40 mph and a ventilation rate of 450,000 cfm, the average CO concentration would be 35 ppm. Under a traffic jam condition, the CO would be 160 ppm with a 600,000 cfm ventilation rate and 225 ppm with a 450,000 cfm ventilation rate. With a power failure where the only ventilation would be due to the piston effect, the CO profile would range from zero at the entry portal to 150 ppm at the exit portal.

Traffic counts were made at the Lincoln Tunnel in New York City and CO data from the permanent monitors in the tunnel were acquired. This information was used to predict the CO level in various sections of the tunnel and to compare the predicted with the actual concentration.

A mathematical model of tunnel ventilation was developed in 1965 by the R&D Division of the Port of New York Authority-Engineering Department. The purpose of this model was to predict the amount of any contaminant in the Lincoln and Holland Tunnels. The model was formulated by balancing air and contaminant inflows and outflows for each sectional length of tunnel. Instead of the finite difference equations used in the MSAR model, the PNYA model employs differential equations which are derived for both ventilation and contaminant profiles. The data generated by both methods should be identical if a sufficiently small length derivative (dl) is chosen. The MSAR model does not require derivation of differential equations.

The carbon monoxide profile of the Lincoln Tunnel-north tube was calculated using the PNYA model. The results were then compared with observed CO values as shown in Figure 22. Agreement between observed and calculated CO profiles is good except at the tunnel portals.

Traffic counts were made in the north tube and in the center tube with both one-way and two-way traffic. Figure 23 shows the results of the north tube calculation both with and without the piston effect. (It should be noted that the chart CO levels are averages for each section since the monitors are located in the exhaust ductwork.) The calculated results are in good agreement with the measured results and are within the accuracy of the CO monitors. Figure 24 shows the calculated and measured CO values for one-way traffic in the center tube. In this case, the calculated

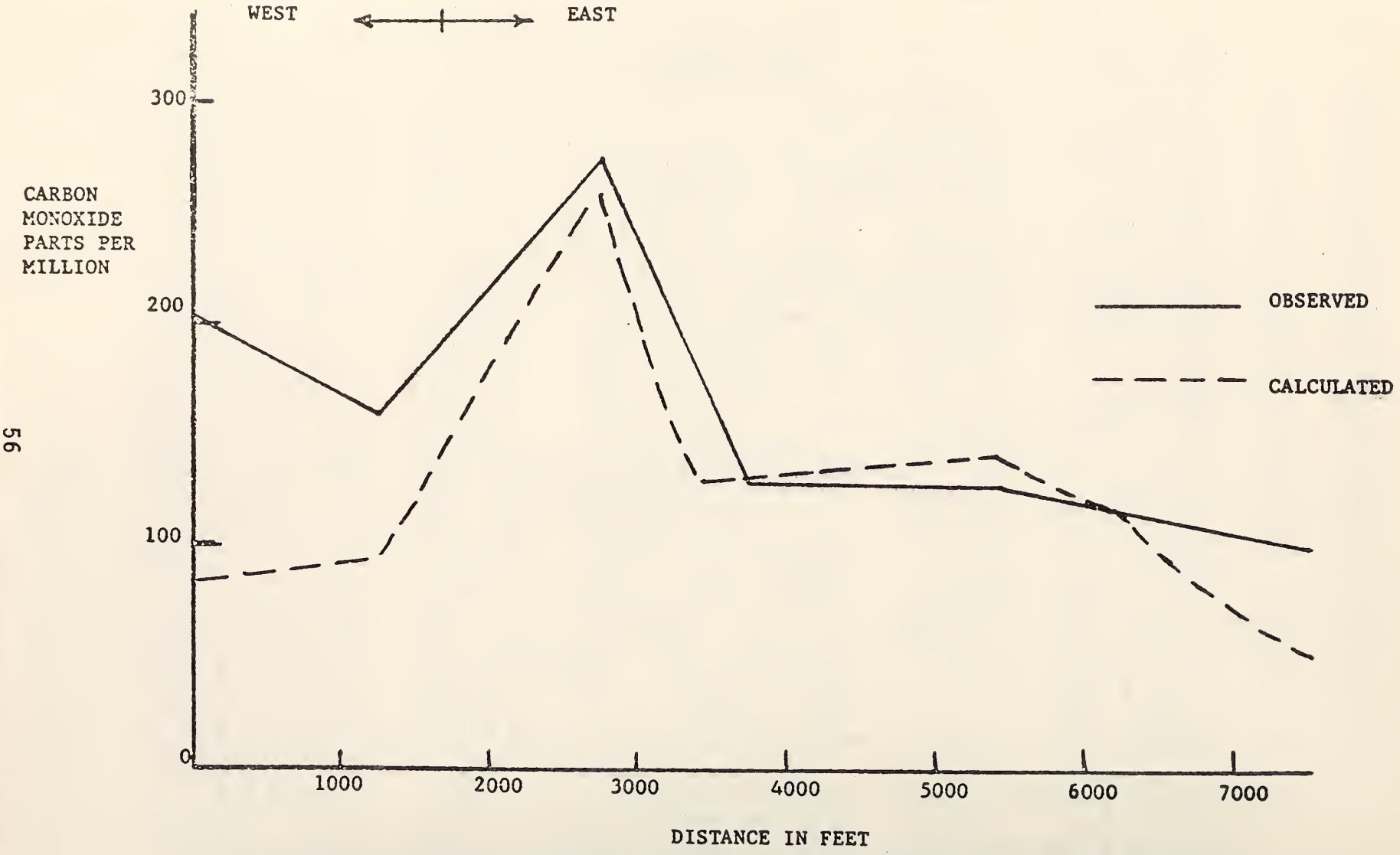


FIGURE 22 - CARBON MONOXIDE PROFILE LINCOLN TUNNEL-NORTH TUBE

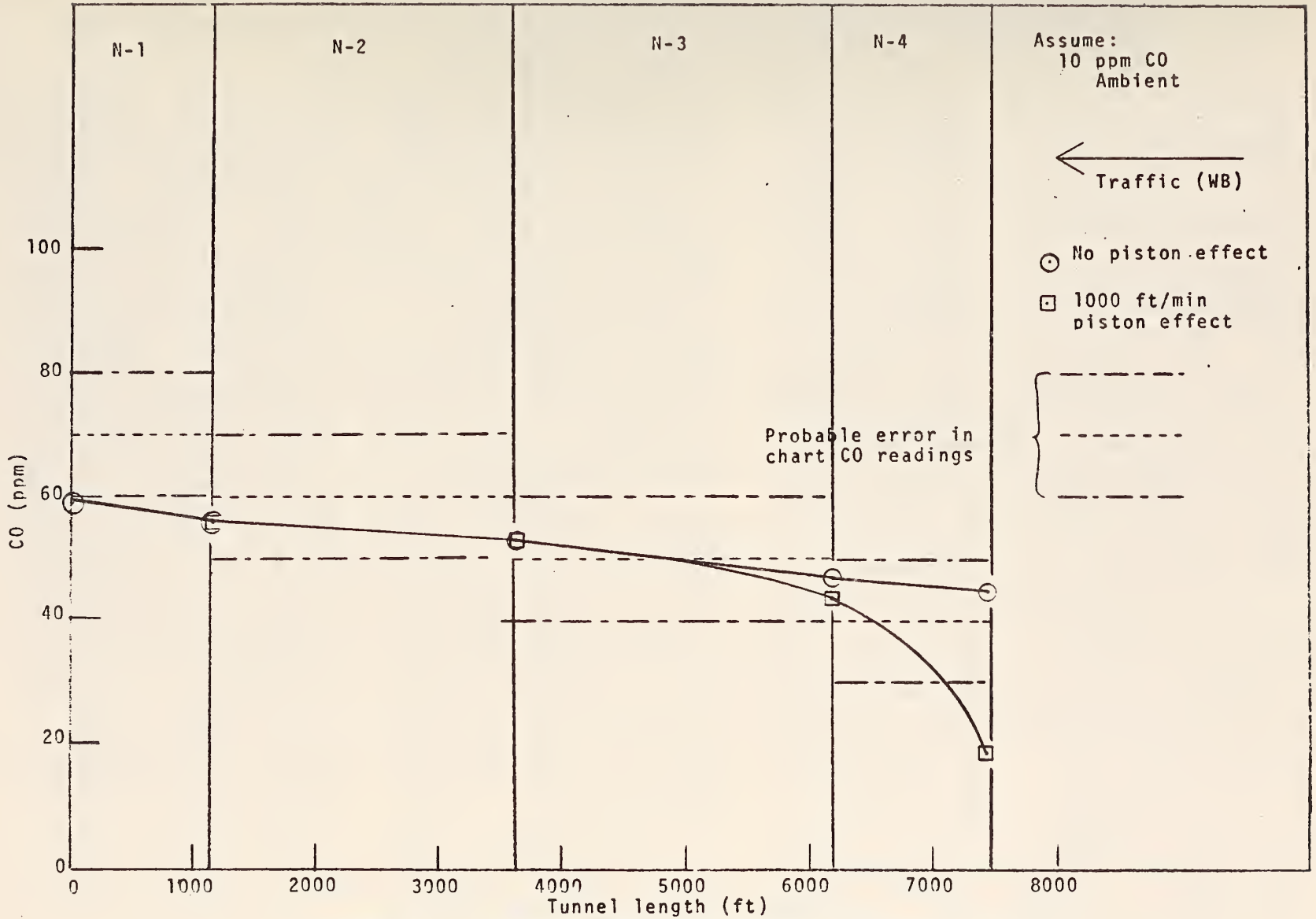


FIGURE 23 - ACTUAL AND CALCULATED CO VALUES FOR THE LINCOLN TUNNEL-NORTH TUBE

concentrations deviated somewhat from the measured concentrations. This was also true in the case where two-way traffic was used in the center tube (Figure 25). However, with the two-way traffic pattern the calculated and measured CO concentrations followed the same general trend. Deviations of the actual values from calculated values could be due to incorrect ventilation rate data, incorrect CO readings, incorrect inlet air CO concentrations or an error in the computer program. However, the latter reason is unlikely since good agreement between actual and calculated values were found in all other tunnels tested as well as the north tube of the Lincoln Tunnel.

The Fort Pitt Tunnel is a dual-tube urban tunnel which carries Interstate Route I-76 into downtown Pittsburgh, Pa. Each tube is 4900 ft long and has a road level grade of 1% except at one end of the West tunnel which has a 3.5% up grade for about 400 ft. (The North portals are on two different levels which correspond to the decks of the approach bridge.) Atmospheric conditions were cloudy, light rain all day, very little wind, temperature 50 to 54°F during the day when actual measurements were made.

A series of 30-minute counts were taken at various times throughout a typical week day. Results showed that the traffic rate varied from 1500 to 1900 vehicles per hour per tube between 9 A.M. and 4 P.M. and 3200 to 3400 vehicles per hour at peak times (4 to 6 P.M. outbound tube and 7 to 9 A.M. inbound). During the night the rate is usually down to 200-400 per hour except when a sports or civic event is scheduled. The ratio of gasoline engine powered to diesel powered vehicles varied from 13/1 in late morning to 66/1 during the evening rush hour. Traffic normally moved through the tunnel at 45 to 55 mph. At peak periods speeds fall to 20-25 mph. Since the average spacing between vehicles is about 20 ft, the maximum tunnel population is 250 vehicles per tube. The population density may increase, of course, in case of a stoppage.

In the Fort Pitt Tunnel, as in most tunnels which employ semi-traverse or semi-longitudinal ventilation with intake fans but no exhaust fans, the air sampling intake lines for the CO monitoring equipment are mounted in niches in the tunnel wall about 9 ft above roadway level. This tunnel employed two monitors per tube; each one located about 350 ft in from the portals or tunnel ends. The recorded signals from each of the four Hopcalite-type detectors are monitored by operating personnel in the control room. During the night the CO level is normally about 10 ppm. During the day it rises to about 50 ppm except at peak periods when it rises to 100 ppm. Peak period level may rise to 250 ppm if fan speeds are not increased in advance of pollution emission increases.

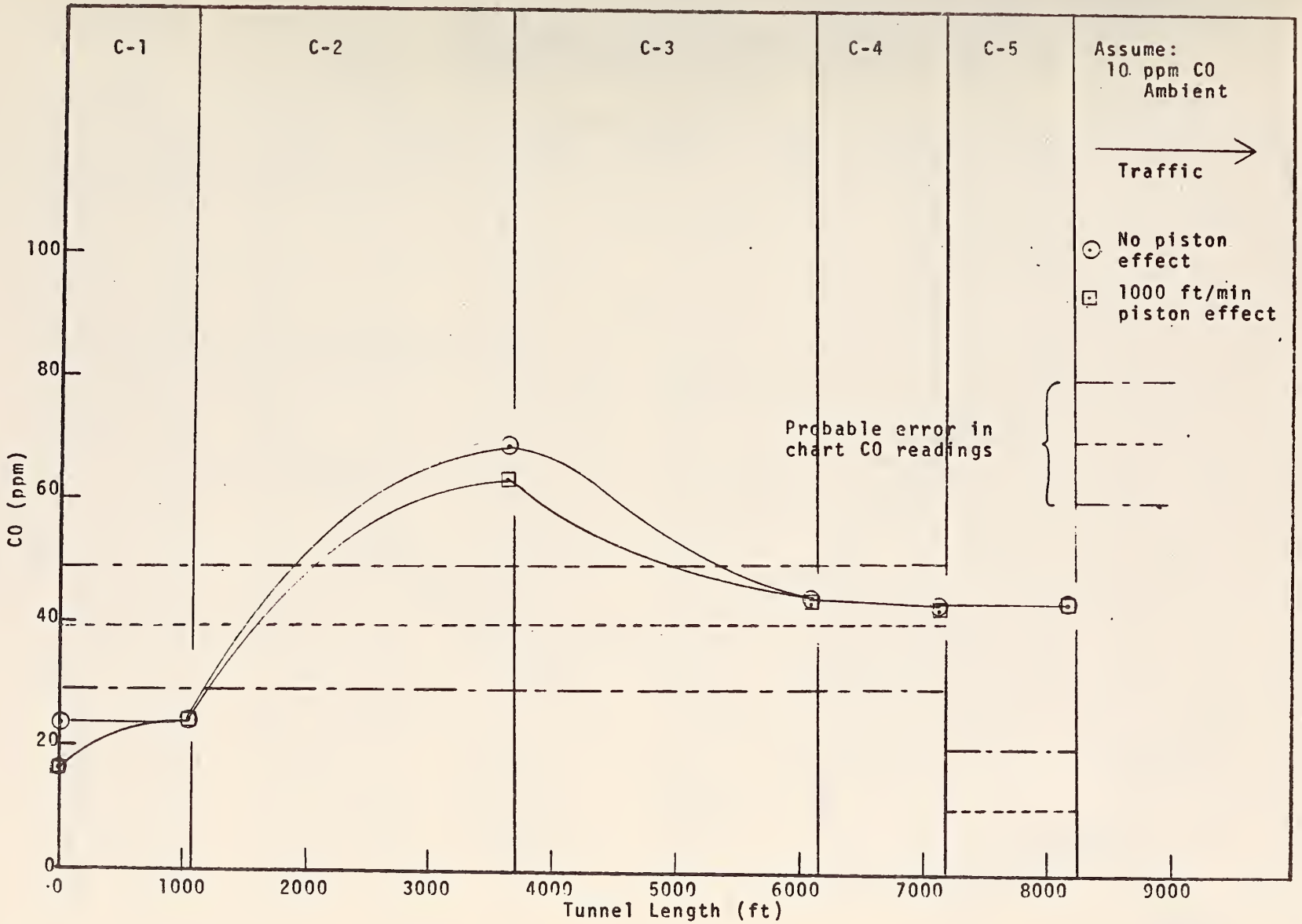


FIGURE 24 - ACTUAL AND CALCULATED CO VALUES FOR THE LINCOLN TUNNEL-CENTER TUBE

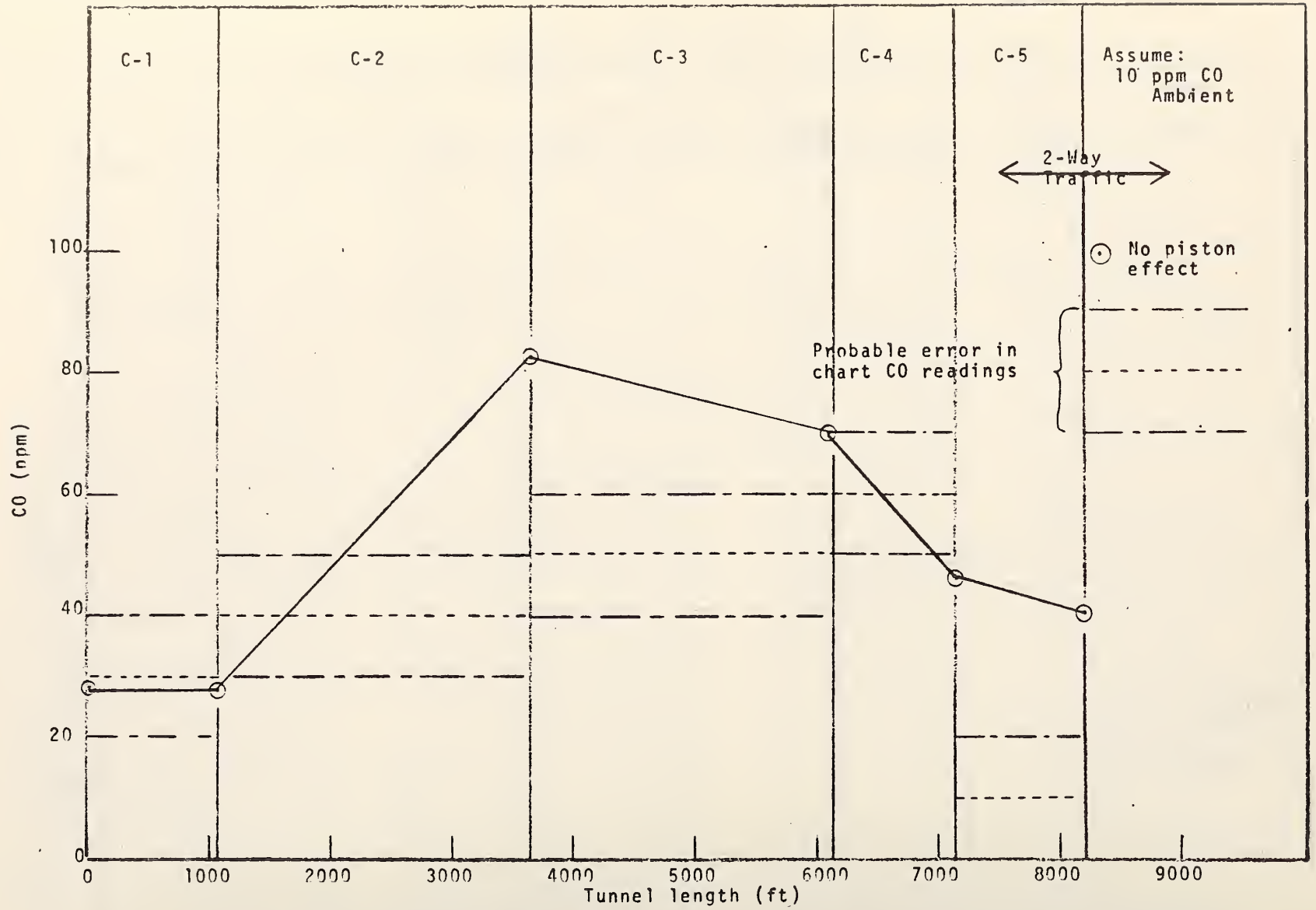


FIGURE 25 - ACTUAL AND CALCULATED CO VALUES FOR THE LINCOLN TUNNEL-2 WAY TRAFFIC

Spot checks of CO content at catwalk levels were made with a portable detector. Readings during off-peak hours agreed with the CO values recorded in the control room. At peak traffic hours, however, the spot check values ranged about 60 ppm higher than those recorded. In a more complete analysis of CO level variations in the Fort Pitt tunnel, it was demonstrated that the CO level in the central portion of the tunnel may be considerably higher than that at the ends (Figure 26).

Each tube contains six fans - three at each end. Only two of the three are used as fresh air input fans. The third fan is used as an emergency exhaust. Fresh air is supplied through ceiling ducts from either end of each tube. Vitiated air is exhausted through the traffic portals. Considerably more air is exhausted via the traffic exit portal due chiefly to the addition of the piston effect. The magnitude of this difference was measured by taking anemometer readings on the catwalk. Air velocity at the inlet portal ranged from about 820 ft/min compared with 1210 ft/min at the exit portal.

Air flow rates are adjusted manually from the control room according to traffic demand. Flow rates range from 121,000 cfm (night-downgrade) to 535,000 cfm (peak-upgrade) with a maximum fan capacity of 714,000 cfm (upgrade tunnel). Each fan can provide for up to 85% of the normal requirement for its particular duct.

Ten-minute observations were carried out at various hours along the tunnel catwalk. Results showed an average noise level of 97 dBC with peaks up to 106 dBC. The peaks were produced by the passage of large trailer and cab type trucks. Operating and maintenance personnel are normally not exposed to these sound levels for extended time periods.

A constant volume air sampler was placed in operation at a point 264 ft from the south portal of the east tube on the catwalk with the sampling inlet away from the stream of traffic. A filter paper disc (MSA Part No. 25310) was used with a sampling flow rate of 15 cfm. The sampler was operated for 5 hours during the off-peak hours (11 A.M. to 4 P.M.). A total of 68 mg of particulates were collected which represents a density of 0.6 mg/m^3.

A 3.2 gm sample of particulates was collected from the floor of the room housing the Fort Pitt tunnel south portal ventilation fans. An analysis of this sample was performed by an emission spectroscopy method. The results are shown in Table 12. Extraction with benzene showed that the sample was 93% benzene soluble (organic).

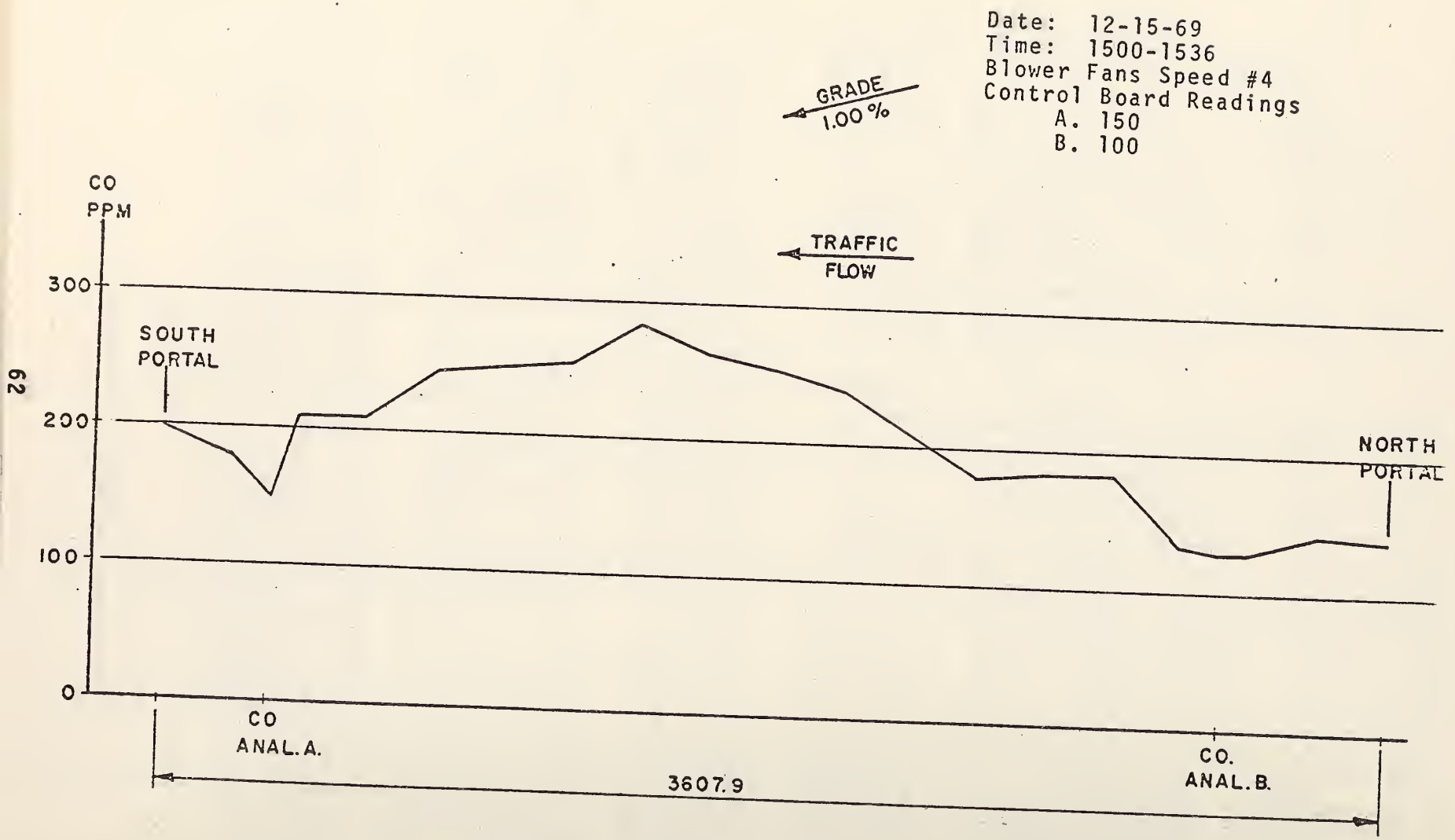


FIGURE 26 - CARBON MONOXIDE PROFILE OF FORT PITT TUNNEL- WEST TUBE

TABLE 12 - ANALYSIS OF MATERIAL COLLECTED FROM VENTILATION BUILDING OF THE FORT PITT TUNNEL*

Component	Concentration
Iron	7.5%
Aluminum	3.6%
Magnesium	1%
Silicon	14%
Boron	90 ppm
Cobalt	10 ppm
Manganese	8000 ppm
Tin	150 ppm
Lead	2000 ppm
Chromium	400 ppm
Titanium	1000 ppm
Nickel	500 ppm
Molybdenum	200 ppm
Vanadium	200 ppm
Sodium	1500 ppm
Niobium	<100 ppm
Calcium	<100 ppm
Zinc	1000 ppm

*This is an analysis of the benzene in soluble fraction of the collected material.

Samples were taken for total hydrocarbons and NO, also. The total hydrocarbon samples were taken in glass sampling bombs and ultimately transferred to the laboratory and analyzed. Samples for NO were collected and analyzed by the Saltzman Method.(33)

Vehicle counts were made in both the northbound and southbound tubes and samples were collected at two locations in each tube. Ventilation rates were obtained from the control room operators and the information was used to calculate the predicted levels based on the computer model and the selected emission rates. The results are shown in Table 13. The predicted and actual CO values agree quite well (± 20%). The NB-1 samples for NO and HC did not agree well with the predicted levels. However, since these are point source measurements and were made near the entry of the tunnel, some differences could be expected. In all cases, the predicted NO levels were equal to or higher than the measured values. This may indicate that NO emission factors are incorrect. In general, however, most of the results agree rather well, but could probably be improved if better emission rates were known for the current car population.

One naturally ventilated tunnel, the Armstrong Tunnel in Pittsburgh, was visited and data were collected on CO concentration and noise level. This two-tube tunnel is located near downtown Pittsburgh, Pa. It carries city traffic a distance of 1350 ft and lies beneath the campus of Duquesne University. Traffic lights are located at the intersections at either end of the tunnel. Since this tunnel has no ventilating fans, it was selected as an ideal location to study piston effect. The tunnel is also used by pedestrians (in one tube only).

The number of vehicles admitted to the tunnel is limited by the cycle of the traffic control lights. In the west tube approximately 18 vehicles/min are admitted while in the east tube the number is about 33 per minute. Traffic speed is maintained at about 30 mph. Backing does occur at the traffic lights. This normally involves 6 to 12 vehicles for times of 30 seconds. Gas/diesel ratio ranges from 10:1 to 20:1. Pedestrian traffic averages 8 per hour with an average walk-through time of approximately four minutes.

Readings taken with a portable Hopcalite detector averaged 50 ppm inside the tunnel with an increase to 200 ppm at the portal at which backed-up traffic occurs. Anemometer determinations of air movement showed that a velocity of 370 ft/min was maintained at sidewalk level with an intermittent flow of 1050 vehicles per hour. Assuming a tunnel cross-section of 435 ft^2, the volumetric flow rate could be as high as 150,000 cfm. The CO output for 18 cars at 30 mph is 18 x

TABLE 13 - FORT PITT TUNNEL TEST DATA APRIL 7, 1971

Sample (1) (No.)	(Point)	Vehicle Count (Per Hr.) Gas	Diesel	Ventilation Fan (x 10^3CFM)	Piston	CO (2) (Gm/veh-mi) Gas - 40 Diesel - 4.0 Model (ppm)	Test (ppm)	NO (2) (Gm/veh-mi) Gas - 4.0 Diesel - 8.0 Model (ppm)	Test (ppm)	H-C (2) (Gm/veh-mi) Gas - 2.7 Diesel - 3.4 Model (ppm)	Test (ppm)
1	NB-1	1732	92	536	200	36	30	4.5	1.8	2.0	0.8
2	NB-3	2196	96	535	200	44	50	5.8	3.8	2.4	1.3
3	SB-2	2976	84	430	250	50	60	5.9	5.9	2.4	3.8
4	SB-1	3468	36	572	200	67	80	8.2	5.3	3.0	5.0

(1) NB indicates northbound tube
SB indicates southbound tube

(2) Estimated emission values for CO, NO and HC from gasoline and diesel engines are shown at the headings of each column. These values were used in calculating the computer model concentrations.

60 gms/mile or 270 gm per tunnel length (1/4 mi). Since vehicles require 30 sec to pass through the tunnel the CO emission rate is 540 gms/min or 15.3 cfm. Assuming a ventilation rate of 150,000 cfm (4,860,000 gms/min) yields a possible average tunnel CO concentration of 110 ppm. Figure 27 shows the measured CO profile. Traffic noise ranged from 88 to 93 dBC.

In conclusion, the computer program appears to adequately predict the pollution level of CO in tunnels as a function of the variables which are fed into the program. Computed values for hydrocarbons and NO appear to be reliable in some cases and unreliable in others. However, emission rates for the contaminants are not as well defined as are emission rates for CO and vary considerably depending upon the mechanical condition and age of the car.

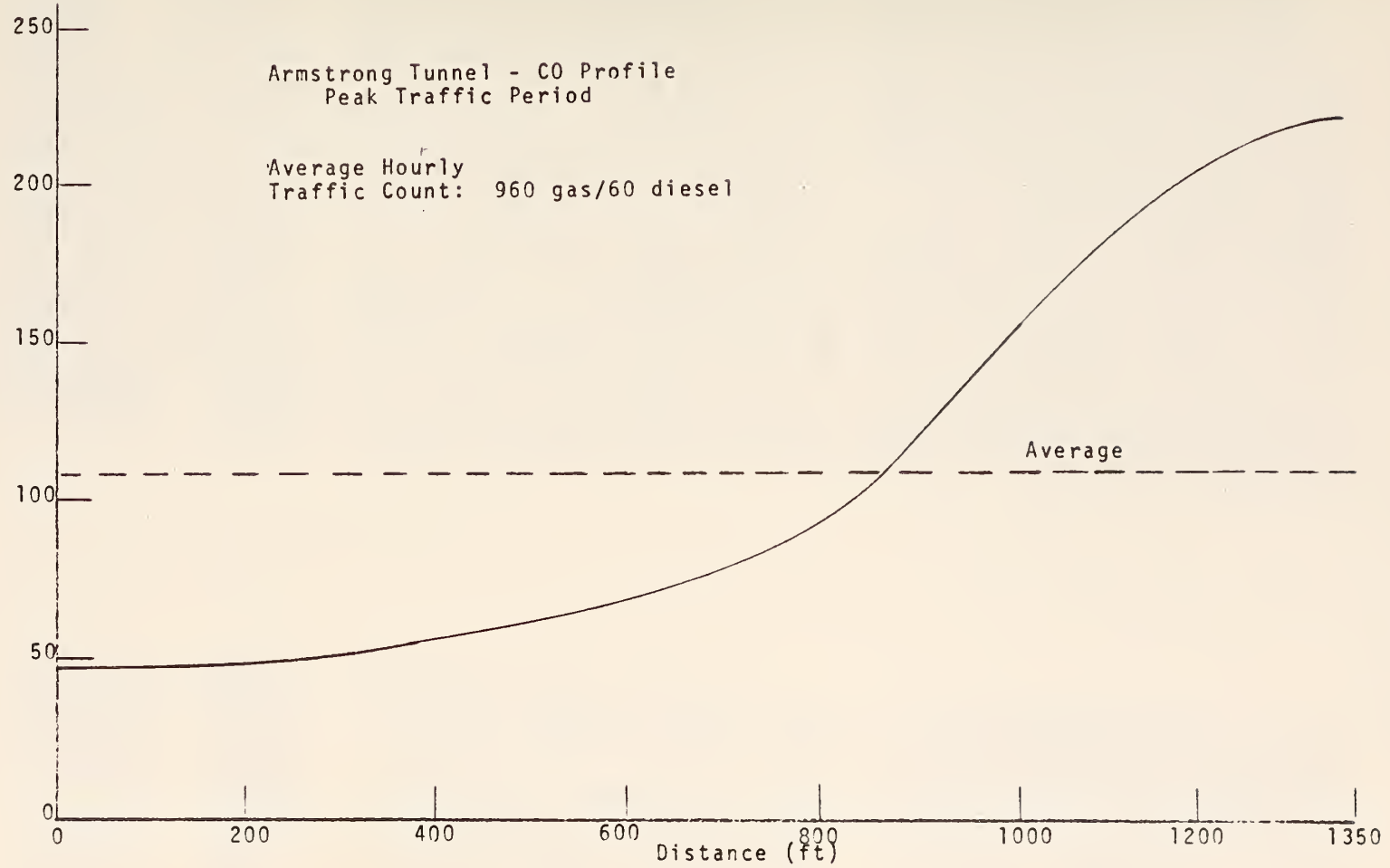


FIGURE 27 - MEASURE OF CO VALUES FOR THE NATURALLY VENTILATED ARMSTRONG TUNNEL

PHYSIOLOGICAL EFFECTS OF TUNNEL CONTAMINANTS

The objectives of this phase of the program were to evaluate the effects of vehicle tunnel impurities on both in-tunnel workers and the transient public, and to set limits for maximum allowable concentrations for manned tunnels as well as safety and comfort levels for unmanned tunnels. Selection of the impurities for which limits were set was based on the contaminants which were found in tunnels and the concentration levels at which these contaminants were present in vehicular tunnels. The Industrial Health Foundation, Inc. of Pittsburgh served as a subcontractor on this phase of the program. The final report from Industrial Health Foundation is included as Appendix I of this report. The selection of specific limits was the responsibility of MSAR and selected limits along with the criteria for selection of these limits were submitted to and reviewed by the Environmental Protection Agency.

Contaminants Which Have Been Found in Tunnel Atmospheres

A number of studies have been made on the contaminants which have been found in vehicular tunnels. The primary source of these pollutants is, of course, the engine emissions from the vehicles in the tunnels. Other sources which contribute a minor portion of the total pollutant inventory include metal and rust from the vehicles, tire wear particles, roadway erosion debris and impurities in the incoming ventilation air. The major constituents of auto exhaust gases are CO_2 and water, but these are not health hazards to tunnel workers or transients. The minor constituents of auto exhaust are CO, NO_x, hydrocarbons, partially oxidized hydrocarbons and particulates. These minor constituents are the materials which pose either a health hazard or a discomfort problem in tunnels. Many of these impurities are toxic and/or noxious in relatively low concentrations.

Table 14 is a composite listing of ranges of tunnel contaminants measured in a number of different tunnels. These values serve to compare relative concentrations and therefore provide a basis on which to select those contaminants for which limits should be set.

Carbon monoxide levels in tunnels frequently exceed the Threshold Limit Value (50 ppm) and occasionally exceed the Short Term Limit Value (400 ppm/15 min). Since CO is the major health hazard impurity in automobile exhaust, limits will be set for this contaminant.

TABLE 14 - MEASURED TUNNEL CONTAMINANTS

Contaminant	Range
CO	54-170 ppm
NO_2	0.05-0.43 ppm
NO_x	0.2-1.63 ppm
Aldehydes(1)	0.05-0.12 ppm
SO_2	0.04-<0.05 ppm
Total particulates	0.424-2.350 mg/m^3
Polycyclic hydrocarbons	
Pyrene	0.04-1.20 $\mu g/m^3$
Benzo(a)pyrene	0.03-0.69 $\mu g/m^3$
Coronene	0.03-0.53 $\mu g/m^3$
Benzperylene	0.09-0.99 $\mu g/m^3$
Metals	
Lead	9.5-44.5 $\mu g/m^3$
Iron	9.5-23.4 $\mu g/m^3$
Zinc	2.2 $\mu g/m^3$
Cadmium	0.04-0.6 $\mu g/m^3$

(1) It has been estimated that formaldehyde accounts for 70-80% of the total aldehyde emissions.

Oxides of nitrogen are present in tunnel atmospheres as a result of oxidation of atmospheric nitrogen during fuel combustion. The NO/NO_2 ratio varies according to the mode of operation but on the average the ratio is in the range of approximately 4/1 to 5/1 in gasoline engines. However, the oxides of nitrogen emitted by diesel engines are higher than that emitted by gasoline engines. Of the two oxides, NO_2 is the more toxic and more irritating. The TLV for NO_2 is 5 ppm, whereas the TLV for NO is 25 ppm. Although these contaminants appear to be present in levels below the safety limits and odor threshold limits, at the present time, there are plans to use certain tunnels for diesel traffic only. For example, the Pittsburgh Port Authority Transit intends to convert an existing trolley tunnel into a mass transit bus tunnel. These buses will be diesel powered and one would predict an increased level of oxides of nitrogen in that tunnel. In anticipation of these problems, it was decided that levels would be set for NO and NO_2.

The other impurity in tunnels which has been observed to exceed the irritation or odor threshold limit is formaldehyde. The irritation threshold for HCHO has been reported to be as low as 0.05 ppm while levels of 0.12 ppm have been reported in tunnels. Authorities on odor have frequently attributed the objectionable odor of auto exhaust to the aldehyde content. Therefore, limits have been selected for formaldehyde which is the major aldehyde emitted from auto exhaust.

Particulate concentrations in vehicular tunnels (2.35 mg/m^3 max) are less than the Threshold Limit Value. However, the two main objections by tunnel users from an esthetic standpoint are odor and haze. In addition to the nuisance factor, it is recognized that particulate material can have a synergistic effect on the physiological actions of other impurities present in air. Therefore, limits have been selected for particulate concentrations in the tunnels.

Other impurities present in tunnel atmospheres include, as two general categories, partially burned hydrocarbons and metals. Benzo(a)pyrene has been of particular concern to the environmental health personnel because of its carcinogenic properties. However, the maximum value measured has been only 0.5% of the TLV. All metals which have been detected are well below the TLV. Lead is the metal that has been measured in highest concentrations and it is only 20% of the TLV. With the advent of unleaded gasolines, the concentration will undoubtedly decrease.

This covers all of the contaminants which have been detected in vehicular tunnels except for SO_2. A cursory comparison of the concentration level versus the odor level would suggest that limits should be set for SO_2. However, the work which provided these values showed that the SO_2 level was present in the intake air rather than as a result of automotive exhaust. Therefore, no limits will be set for SO_2.

Selected Contaminant Levels for Vehicular Tunnels

In manned tunnels, police officers are located at three or four locations in the tunnel. These officers spend two hours in the tunnel and two hours out of the tunnel, so that during an 8 hr work day, they are exposed to the tunnel atmosphere for a total period of four hours. Personal interviews with these employees revealed that they frequently experience headache, tiredness and eye irritation. Personal observation of these officers as they came off duty during or immediately following rush hour traffic indicated that they did indeed have eye irritation.

Maintenance personnel represent another work group which is exposed to tunnel atmospheres. Routine maintenance such as replacement of lights, repair or replacement of tile and washing of the tunnel walls is scheduled during off-peak periods. In dual tube tunnels such as the Pennsylvania Turnpike Tunnels, Baltimore Harbor Tunnel and others, two way traffic is shunted through one tube during the late evening and early morning hours while the other tube is being washed or repaired. Emergency maintenance within the tunnel is not frequently required and in general requires that maintenance personnel be present in the tunnel for only a short time.

Specific Limits for Manned Tunnels - Over 200 reports, reviews or abstracts, both domestic and foreign, on the physiological effects of selected tunnel impurities have been reviewed. Some of the information includes consideration of synergistic effects due to particulates, other impurities and noise (in the case of CO) while other studies do not. In many cases, the conclusions on physiological effects are vague or even contradictory.

Three of the studies were directly pertinent to setting of limits for manned tunnels in that the studies involved clinical examination of personnel who had spent greater than 10 years working in tunnels. One of the reports stated:

> "No mortality or morbidity from primary lung cancer was found among a group of 97 retired tunnel police officers who had worked within

the Holland Lincoln Tunnels, and had been in retirement for at least 10 years after 25 years of active service. No case of primary lung cancer was found among the 25 retired police officers studied who had died during this same retirement period. Among the 16 living nontunnel retired police officers included in this study, there is one with primary lung cancer successfully resected 11 years ago. The interval between initial exposure in the tunnels and the time of this study was at least 18 years and as long as 37 years; in 89.7%, the interval was over 30 years."(34)

The second article stated:

"Results are presented of an epidemiologic investigation of the respiratory symptons and pulmonary functions of a group of men exposed to automobile exhaust in a road tunnel. Chronic nonspecific respiratory disease was more prevalent in men who had worked in the tunnel for more than 10 years than in those with a shorter time of employment. Chest colds were also more frequent in this group. The size of the sample did not permit proper assessment of the effect of age or cigarette smoking on this population. The maximal expiratory flow rate, as measured with the Wright peak flowmeter, was significantly lower in the workers with chronic nonspecific respiratory disease than in the rest of the workers studied."(35)

A third stated that:

"Examination of a group of 156 Holland Tunnel traffic officers exposed throughout a period of 13 years to an occupational carbon monoxide exposure averaging 70 ppm did not reveal any evidence of injury to health contributable to carbon monoxide exposure."(36)

On the basis of the work by Speizer, one may conclude that some adverse effects on the respiratory system are imposed by exposure to tunnel impurities.

In spite of the large volume of information available on physiological effects of air contaminants on the human being, it is still extremely difficult to select firm standards for employees in manned tunnels due to the conflicting data which are presented. However, this dilemma

has apparently been solved by the Occupational Safety and Health Act of 1970, Public Law 91-596.[37] This Act sets standards "to assure safe and healthful working conditions for working men and women". As part of this Act, concentrations are set for air contaminants including CO, NO, NO_2, HCHO and particulates (oil mist). These values are:

Contaminant	Allowable Concentration	Time Weighted Avg. Limits[38]
CO	50 ppm	75.0 ppm
NO	25 ppm	37.5 ppm
NO_2	5 ppm	10.0 ppm
HCHO	3 ppm	6.0 ppm
Particulates (oil mist)	5 mg/m^3	10.0 mg/m^3

Although the Act does not make allowances for less than 8 hr exposure periods, the TLV levels do provide for a time weighted average. By definition, time weighted averages permit excursions above the TLV provided they are compensated by equivalent excursions below the limit during the work day. In some instances it may be permissible to calculate the average weekly concentration for a workweek rather than a workday. The degree of permissible excursion is related to the magnitude of the TLV of a particular substance as shown below:

TLV (ppm)	Permissible Excursion Factor
0-1	3
1-10	2
10-100	1.5
100-1000	1.25

It is therefore recommended that these time weighted average limits be adopted as standards for manned tunnels since tunnel personnel are not exposed for a full 8 hr workday.

Most tunnels are designed to maintain CO levels at less than 100 ppm and in general, a warning light is activated in the fan control room when the level goes above 250 ppm. During rush hour traffic, CO levels in the range of 350 ppm are not unusual in some tunnels. It is obvious that these levels significantly exceed the above recommended values for manned tunnels. In such cases, the workers are exposed to levels exceeding the Occupational Safety and Health Act of 1970 and some remedial action must be taken to bring these tunnels within the limits as set forth by the Act.

The Act does allow these limits to be exceeded "in cases where protective equipment or protective equipment in addition to other measures" are provided. Alternatives to maintaining levels at less than the specified limit should be considered since with appropriate fan operation these levels can be maintained in most tunnels for 18-20 hrs of a 24 hr day. Some tunnel authorities have already considered alternatives:

1. Baltimore Harbor Tunnel Authority considered the use of closed circuit television surveillance as an alternative to having personnel in the tunnel. In the event of an accident or breakdown as indicated by the closed circuit television system, maintenance men, firemen or police officers would immediately enter the tunnel to rectify the problem. However, the authority ultimately rejected the idea with the reasoning being that men stationed in the tunnel could react more rapidly to potentially hazardous situations such as accidents, fires and so on.

2. The Port Authority of New York City has installed closed circuit television in the Lincoln Tunnel. However, they still maintain police officers in the tunnel for rapid response to fires, breakdowns, etc. They are currently building a prototype trolley car which would be constantly manned by a police officer at each portal. In the event of a problem witnessed on the closed circuit television, the car would be rapidly dispatched to the scene of the problem. Although the officer will not be stationed in the tunnel, it is highly likely that he will be exposed to concentrations above the specified limit at the exit portals as a result of the piston effect of cars exhausting contaminants through the portals.

These two aforementioned measures involve removing the officers from the tunnel, and it must be admitted that this does increase the reaction time to an incident in the tunnel.

Other measures which would be feasible would include:

1. A direct air supply to the officers' cubicle to provide clean, outside air

was tried in at least one tunnel, but the inlet vents were plugged up by the officers during the winter due to the chill factor of the cold air blowing in.

2. A portion of the tunnel air could be purified and forced into the cubicle. The purification system would remove CO, odorous hydrocarbons, oxides of nitrogen and particulates. Feasible processes to do this have been evaluated under this contract in regard to purification of tunnel air for either recycle or exhaust to the atmosphere.

In summary, the recommendation is made that impurity limits in manned tunnels conform to the Occupational Health and Safety Act of 1970 with the additional provision that the time-weighted limits established by the American Conference of Governmental and Industrial Hygienists be used. It is recognized that these limits are currently exceeded during rush hours in all tunnels and even during non-peak hours in some tunnels. If these recommendations are adopted, then remedial action must be taken to bring the tunnels within allowable limits. These actions may include traffic control, changes in tunnel ventilation procedures, purification of tunnel air or individual respiratory protection.

Unmanned Tunnels - The period of exposure (5-15 min/day) of the traveling public in unmanned tunnels is significantly less than the period of exposure (4 hrs/day) of police officers in manned tunnels. Therefore, the basic premise is made that pollution levels in unmanned tunnels should be set to provide a comfort level. Of course, a safety level must also be considered, but these levels can be higher than those set for manned tunnels since the period of exposure to the polluted tunnel environment is much shorter. Safety levels and comfort levels are discussed separately in the two subsequent subsections.

The pollutants which are considered in unmanned tunnels are the same as those considered in manned tunnels, i.e., CO, NO, NO_2, HCHO and particulates. Since the residence time of an individual in a tunnel is relatively short (5-15 min), then safe levels for most of the contaminants can be increased over those limits set for manned tunnels. It must be remembered that if one contaminant is allowed to increase, then all other contaminants increase proportionately according to their relative concentrations in auto exhaust. However, if internal purification which is being studied as part of this program proves to be feasible, removal of selected contaminants would be possible.

Prior to setting safe limits for unmanned tunnels, "safe limits" must be defined. The definition used in this case refers to levels at which short term exposure will not create any physiological effects on the individual. One of the problems in setting short term safe limits is that limited work has been done in this field, and no systematic rationale has been developed for relating Threshold Limit Values, which are set for long term exposures, to short term exposures. The American Industrial Hygiene Association, The Pennsylvania Department of Health and the Aero Medical Association have attempted to set tentative standards and at this time this is the only established information which can be reliably quoted.

Table 15 lists Threshold Limit Values and Short Term Limits (AIHF) which have been set for the selected tunnel pollutants. It is obvious from Table 15 that the number of Short Term Limits which have been set are significantly fewer than the number which have not been set. However, the tunnel engineer needs values to design to and other data exist which can be used to set tentative limits.

TABLE 15 - TLV AND STL FOR SELECTED POLLUTANTS

Pollutant	TLV	STL (ppm) 5 min	10 min	15 min	30 min
CO	50 ppm	--	1500	1000	800
NO	25 ppm	--	--	--	--
NO_2	5 ppm	35	--	25	20
HCHO	2 ppm	5	--	--	--
Particulates	5 mg/m^3	--	--	--	--

The assumption is made that during rush hour traffic with a stop and go situation, the time to traverse a tunnel could be of the order of 15 min. The standard curves for effects of various carbon monoxide exposures as a function of time shows that at 500 ppm no perceptible effects occur within 15 min. Nitric oxide (NO) is a simple asphyxiant and therefore levels significantly higher than the TLV should be tolerable. However, in the absence of any firm values to support this conclusion, it is recommended that the STL for NO be set at 37.5 ppm. The STL for NO_2 (15 min) has been tentatively set at 5 ppm. This could cause temporary eye and nasal irritation but no permanent physiological damage. Short Term Limits for formaldehyde has been set at 5 ppm for 5 min. The literature states that levels above 5 ppm are severely irritating and therefore a 5 ppm STL is recommended for 15 min. exposures. Particulates are the only non-gaseous

impurities which are being considered for STL values. We do not recommend a level higher than the TLV for particulates, i.e., 10 mg/m^3.

In summary, it is difficult to set Short Term Limits for tunnel pollutants due to the lack of specific data on short term effects. However, using the data which are available along with what is believed to be reasonable extrapolations of related data, the limits which have been selected are as follows:

CO	-	500 ppm
NO	-	37.5 ppm
NO_2	-	5 ppm
HCHO	-	5 ppm
Particulates	-	5 mg/m^3

Comfort level, as used in this case, is defined as that level of contaminant which produces no irritation, sense of unpleasant odor or physiological effect such as minor headache. The "comfort level" varies from person to person depending upon his sensitivity to a given contaminant. Individuals with certain allergies may be particularly sensitive to specific contaminants. Some individuals are more sensitive to odors than are others. These are normal differences that exist among the human population, so in general, odor threshold levels or irritation levels have been selected on the basis of the sensitivity experienced by the major portion of the public.

Carbon monoxide is colorless and odorless and therefore creates no sensation odor or eye or nasal irritation. Significant levels of carbon monoxide over certain periods of time can cause headache. However, assuming a maximum again of 15 minutes residence time in a tunnel, a level of 1000 ppm is certainly well within the tolerable range. Nitric oxide (NO) is also a colorless gas with a slightly sweetish taste or odor at high concentrations. No data were found on either the odor threshold limit or the irritation threshold limit, hence for the present time the TLV of 25 ppm will be used as the comfort limit for NO.

NO_2 exhibits an undesirable odor and is a strong irritant. The odor threshold limit has been reported to be 1-3 ppm and the odor is characteristic and distinct at 5 ppm. The recommended comfort limit for tunnels should be 1-3 ppm. Formaldehyde is also an odorous and irritating compound. Most references quote an odor threshold limit of $\sim$1 ppm, although this seems to vary greatly among individuals. Eye and nasal irritations have been reported at levels of 2-3 ppm HCHO. For a comfort level in tunnels, we recommend a level of 1 ppm.

Particulates in tunnels can be odorous due to their own chemical composition or from odorous gases absorbed on the particulate surface. Particulates can also have an irritation effect particularly through deposition in the eyes. However, the most significant effect on comfort is probably due to the haze effect of particulates. No data was found on the correlation of particulate concentration versus visibility in tunnels. Spot checks made by MSAR personnel at the Baltimore Harbor Tunnel and the Fort Pitt Tunnel showed particulate concentrations of approximately 0.6 mg/m^3 with the particle size ranging from <1 micron to about 5 microns. At this concentration level (0.6 mg/m^3), the "haze level" was low and the visibility was quite good. However, we hesitate to select this concentration as a firm value for tunnel comfort. In the absence of sufficient data, we have decided that a satisfactory level cannot be chosen at this time.

Summary of Recommended Levels

Tentative pollutant concentration levels have been chosen for manned tunnels and for unmanned tunnels. In the latter case, both safe and comfortable levels have been chosen. These levels are summarized in Table 16.

TABLE 16 - TENTATIVE POLLUTION LEVELS FOR TUNNELS

Pollutant	Manned Tunnels	Unmanned Tunnels Safety Level	Unmanned Tunnels Comfort Level
CO	75 ppm	500 ppm	1000 ppm
NO	37.5 ppm	37.5 ppm	25 ppm
NO_2	10 ppm	5 ppm	1 ppm
HCHO	6 ppm	6 ppm	1 ppm
Particulates	10 mg/m^3	10 mg/m^3	N.R. (1)

(1) N.R. - No recommendation due to insufficient information.

The levels which have been set for manned tunnels were dictated by the Occupational Safety and Health Act of 1970; there would seem to be little reason to question these values since they are required standards set by the Federal Government. The safety and comfort levels which were chosen are, of course, subject to some question since little data exists on short term exposure limits.

EVALUATION OF POLLUTANT REMOVAL METHODS

There are two potential reasons for development of methods and systems for purification of tunnel atmospheres. One of these reasons is to purify the atmosphere within the tunnel itself, while the other reason is to improve the quality of the exhaust air from the tunnel. In relation to purity of the air within the tunnels, one reference[39] which was found involves recycle of tunnel air. This system catalytically oxidized CO to CO_2 with Hopcalite followed by condensation of CO_2 and water at liquid nitrogen-liquid oxygen temperatures (Figure 28). The boil-off of the liquid air during cooling provided fresh air for the tunnel. No claim was made for removal of hydrocarbons, particulates and so on. One other reference was found on recycle of tunnel air.[40] This system incorporated wet scrubbing for particulate removal, catalytic oxidation for CO removal, a deacidification unit to remove CO_2 and a condenser. This article claimed that Neutrotecnicia Italiana S.R.L., Milan manufactured these units commercially. MSA Italiana is located in Milan and one of the MSA representatives in the Milan office was requested to procure information from the referenced company. The MSA representative reported that the company stopped its activity in November 1968.

Patent Development Associates, under subcontract to MSAR, reviewed the state-of-the-art of applicable control technology. PDA also made an economic evaluation of selected control measures which might be adaptable to purification of tunnel atmospheres. The result of this study is presented as part of this section. It should be noted that the PDA study was made mid-way through the overall program and therefore some of the emission standards or criteria which are quoted may have changed since that time. It must also be kept in mind that the economic evaluations which are presented are for hypothetical cases and do not necessarily apply to any specific existing or planned tunnel; these economic evaluations are presented merely to show the relative cost of tunnel air purification or recycle versus direct ventilation.

As a result of the survey, certain control techniques were selected for evaluation. The test system and the control techniques which have been tested are also presented in this section.

State of the Art - Applicable Control Technology

Historically, emission control technology was developed as a set of empirical solutions to specific industrial problems in diverse industries and areas. The acceleration of technical and industrial interest in pollution control *per se*

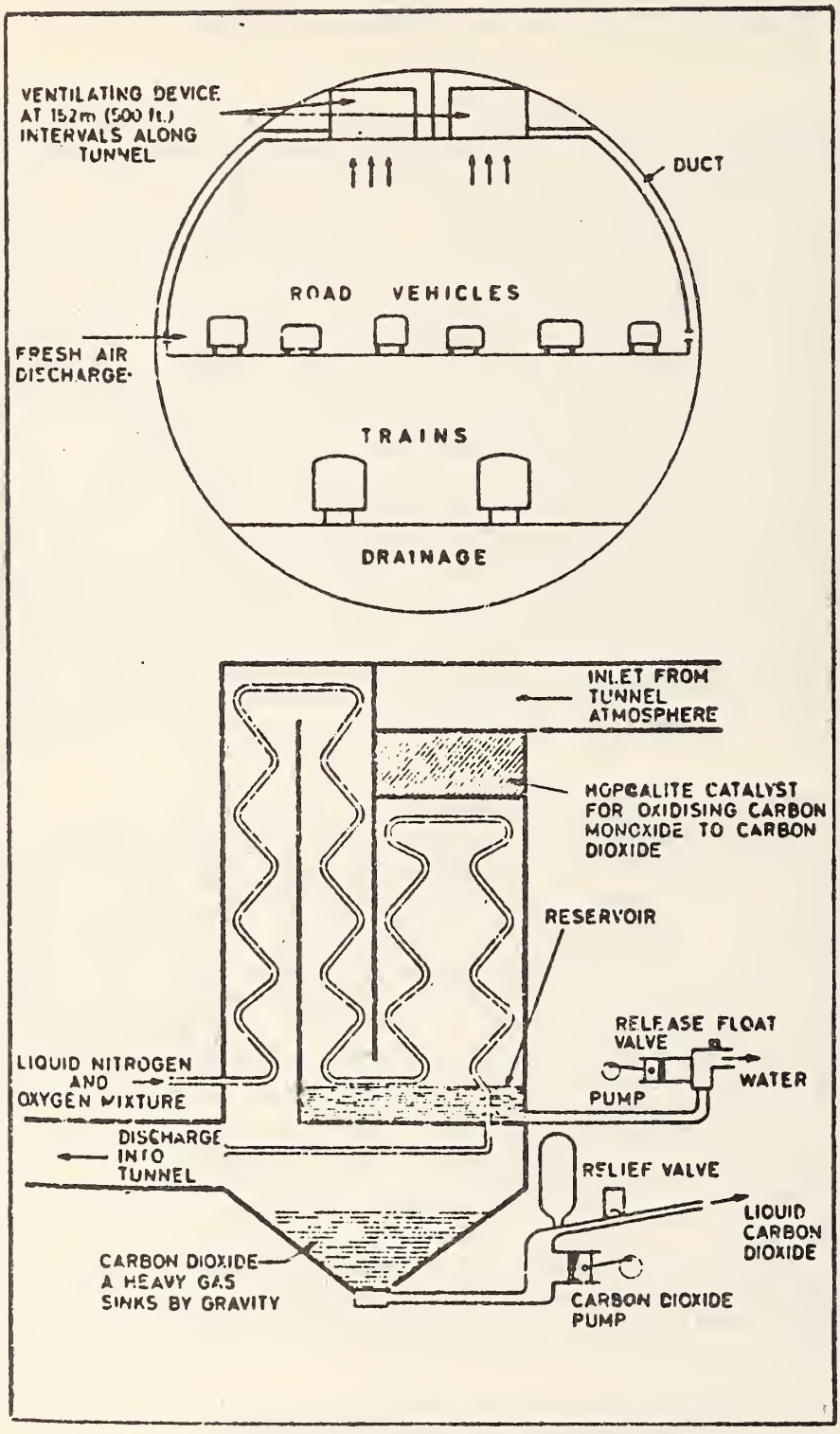


FIGURE 28 - SCHEMATIC DIAGRAM PROPOSED BY SIR BRUCE WHITE(39)

in the last two decades has forced continuing collection and critical examination of the technology available for accomplishing such control, and several comprehensive reviews have recently appeared.

The Air Pollution Engineering Manual[41] is an extensive compilation by the Air Pollution Control district of the County of Los Angeles of control problem hardware solutions and design approaches by type of industrial emission and industry. This reference includes in-depth review of the supporting theory for the design and selection of control method and equipment for particulate removal (inertial separators, baghouses, electrical precipitators) and gaseous pollutants (thermal and catalytic incineration, adsorption, condensation, scrubbing).

Perhaps the best basic text in the new pollution control technology field is Air Pollution[42] Volume III: Sources of Air Pollution and Their Control of this primary work contains the most complete and detailed review of equipment design procedures and capabilities. Another state-of-art review is Volume II: Control Equipment of the Air Pollution Manual[43] which covers industrial control equipment in the same technology categories of inertial separators, baghouses, etc. given above. An abbreviated treatment of theory and design procedures indicates the empiricism of large areas of current equipment selection procedures. The statement made in this reference that "when the process is on the drawing board and the collector is to be specified as part of the plant design, the prime recourse is to experience, on similar plants and processes" is a realistic appraisal of many areas of present control technology art. Much of the information obtained by "experience" has been and is confined to equipment vendor or industrial files, but the increase in enforcement efforts and independent research and publication should eventually force such data into the open literature. At the present time, much of control equipment design art and technology is held by vendors on a confidential basis. One result of this situation is frequent equipment overdesign to compensate for performance uncertainty, with attendant cost and space excesses, and this situation applies to some of the applicable control technology for the tunnel problem.

Applicable Tunnel Pollution Control Technology

Control technology possibly applicable to the problem of pollutant removal in the ventilation of vehicular tunnels must be evaluated in the context of the probable system constraints. Initial review of tunnel-contained dilute automotive exhaust pollution indicate the following parameters

to be potentially significant:

1. Multi-pollutant removal requirements.
2. Blower head loss limitations, particularly in existing tunnels.
3. Large air volume handling requirements.
4. Relatively low pollutant concentrations.
5. Relatively low pollutant emission rates.

Thus, applicable control techniques should have low or zero pollutant threshold sensitivity, be capable of being designed into high-throughput, low-loss equipment configurations, and preferably be functional for more than one component or type of pollutant. Unfortunately, most processes capable of treating large volumetric flows at very dilute pollutant concentrations are normally single-purpose operations, as typified by electrostatic precipitation. For the gaseous components, the control processes that appear likely to satisfy the above-noted general criteria are: adsorption, catalytic oxidation, and absorption. For the particulates, applicable processes include electrostatic precipitation, and inertial or wet-scrubbing. It is obvious that a combination of control operations will be needed to cover the spectrum of pollutants and concentration levels present in diluted automotive exhaust gas.

Table 17 presents a summary of the comparative process capabilities for the probably-applicable control technology as they apply to the tunnel pollution problem. An inspection of Table 17 shows that very few of the standard control operations appear to have unqualified applicability to the tunnel pollutants within the general constraints of the problem. The two operations that appear to be technically applicable without apparent limitations or additional research are electrostatic precipitation for the particulates, and adsorption for the hydrocarbons.

The state of the art of available control technology will be reviewed below with respect to the principal classes of pollutants, and the processes that would normally be used for removal of each pollutant. Because of the multi-functionality of several of the operations considered, process discussion emphasis will be placed on the primary pollutant applicability as shown in Table 17.

Carbon Monoxide and Hydrocarbons

In terms of the relative magnitude of pollutant loadings, CO and unburned (including partially-oxidized) hydrocarbons are the major constituents in auto exhausts, as shown in Table 18, taken from Stern[42]. In addition to the emissions shown as contributed by blow-by and exhaust, the

TABLE 17

COMPARATIVE PROCESS CAPABILITIES

Capability	Adsorption	Catalytic Oxidation	Absorption		Electrostatic	
			Convent.	Spray	Dry	Wet
Low ΔP 1" H_2O		X,R		X	X	X
Ambient Temp. Operation	X	X,R	X	X	X	X
Trace Conc. Removal	X	X,R	X,R	X,R		X,R
Particulates			(X)	(X)	X	(X)
CO		X	$(X)_c$	$(X)_c$		
Hydrocarbon	X	(X)	X	X		(X)
Oxygenated HC	X	(X)	X	X		X
NO_x	(X)	(X),R	$(X)_c$	$(X)_c$		(X)
Problems	(1) Regenerative (2) Requires pre-filter	(1) Requires R&D (2) Requires aux. part. control (3) Poisons	(1) Gas saturation (2) R&D required (3) Liquid disposal problem			(1) Gas Satn. (2) Liquid disposal problem

(X) Limited Efficiency
$(X)_c$ With Chemical Reaction
R Further R&D Required

TABLE 18

COMBUSTION-RELATED VEHICULAR EMISSIONS

	Emissions			
	Blow-by		Exhaust	
Component	Concentration	Wt. (lb/day)	Concentration	Wt. (lb/day)
Carbon monoxide	Trace	Nil	3.12%	4.160
Oxides of nitrogen	Trace	Nil	850 ppm	0.202
Hydrocarbons				
Paraffins				
C_1-C_5	3150 ppm	0.033	130 ppm	0.034
C_6 and heavier	4780 ppm	0.072	155 ppm	0.073
Olefins				
C_2-C_4	230 ppm	0.001	500 ppm	0.079
C_5 and heavier	1420 ppm	0.017	30 ppm	0.012
Aromatics				
Total less benzene	5150 ppm	0.089	190 ppm	0.100
Benzene	270 ppm	0.003	75 ppm	0.029
Acetylenes	60 ppm	0.001	285 ppm	0.036
Total hydrocarbon	15060 ppm	0.216	1365 ppm	0.363

Mass emissions calculations based upon 31.0 ft^3/min. STP average exhaust gas flow rate or 71.0 ft^3/mile, STP. Adapted from Rose, 1966 (3).

evaporative losses from the fuel tank and carburetor add another 20 to 40 percent to the hydrocarbon content of the total emission. Nevertheless, Table 18 indicates the various pollutant contributions, exclusive of the particulates, and CO and hydrocarbons are the most significant. These two pollutant components are usually grouped together by reason of the fact that they are present because of incomplete oxidation, and completion of oxidation by secondary means will eliminate them from the exhaust. It should be pointed out, however, that for non-oxidative techniques such as adsorption, these two components will not behave similarly.

The two general methods of oxidative disposal of carbon monoxide and hydrocarbons are:

(a) Catalytic oxidation
(b) Direct thermal or flame incineration

These two methods of combustion completion have been used as source control techniques for automotive emissions, and sufficient experience has been obtained on their use to provide a guide to their possible use on tunnel air.

Catalytic Oxidation

Basic research on the susceptibility of homologous series of hydrocarbons to catalytic oxidation has been carried out by Accomazza[44] and Caretto[45], while the industrial aspects of design, economics and operation have been reviewed by Brewer[46] and Werner[47]. Werner classifies the commercial catalytic afterburning (CAB) catalysts as (a) active metal/metallic carrier, (b) active oxide/oxide carrier, and (c) active metal/oxide carrier. Poisoning or loss of activity is one of the major problems with CAB materials and both Brewer and Werner provide information on the nature of poisons for the various types of catalysts. Miller[47a] reported the results of laboratory tests of the effect of support geometry on oxidation performance over a volumetric space velocity (gas volume/bed volume) range of 30,000 to 175,000 $hr.^{-1}$, concluding that an open-structured geometrically regular support was optimum. However, large volume costs for this catalyst ($300/cu.ft.) appear to be prohibitive. Further work on support geometry was reported by Leak[48] who tested alumina-coated steel wool filamentary catalytic mufflers on auto exhaust. A dual-catalyst system of vanadia plus copper chromite on the alumina had the highest activity for CO and hydrocarbon removal. Industrial and economic data on CAB installations is provided by Lauber[49] and Krenz[50] while design procedures are given by Dey[51].

Research on a wide variety of possible exhaust catalysts has been published including vanadium-alumina [52][53], promoted uranium oxides[54] and combinations of vanadium and copper oxides with noble metals[55]. A large amount of relevant background art on catalytic mufflers is contained in the U. S. Patent Office, Class 23/Subclass 2. This file has been reviewed, and it was found that most of the development effort in this area has been undertaken either by chemical companies manufacturing tetraethyl lead, or petroleum companies. Table 19 summarizes the features of several of the recent catalytic muffler patents for treatment of auto exhaust.

Catalytic oxidation normally involves temperatures in the range of 400°-800°F[56]. Much of the conventional technology of catalytic oxidation derives from commercial application to the removal of organic vapors from industrial process emissions at these elevated temperatures[57], and automotive exhaust catalyst temperatures are of the order of 600°F. In tunnel gas processing, the operation of a catalytic oxidation process at temperatures above ambient will incur an economic burden proportional to the degree of temperature elevation. The thermal penalty in the case of a recycle gas operation is doubled, because the gas not only has to be heated to reaction temperature, it has to be re-cooled to ambient circulation temperature. Thus, with large circulating air volumes, an optimum system will require a particularly low, or preferentially ambient-temperature catalyst.

Heat evolution in catalytic oxidation application does not appear to be a potential problem at the low combustible concentration levels expected in tunnel gas. On the other hand, combustible levels are too low to support reaction at temperatures above ambient. The ambient-temperature requirement delineates an operational area in which only limited work has been done. Low-temperature catalytic oxidants for CO and hydrocarbons consist of hopcalite, supported noble-metal catalysts, and some newly developed transition and noble-metal/activated carbon combinations.

Low-temperature catalytic oxidation of CO and unburned hydrocarbons at simulated auto exhaust conditions was studied by Cannon and Welling[58] for a very wide range of metal and support combinations at temperatures below 350°C. While a large group of catalysts appeared to have satisfactory activity in this temperature range, only one catalyst, a commercial 60% manganese oxide/40% copper oxide, had a threshold oxidation temperature of 25°C and a complete oxidation (100%) efficiency at an operating temperature level of 25°C for an hourly space velocity of 10,800. All other catalytic materials tested had threshold

TABLE 19

REMOVAL PROCESS SUMMARY
CATALYTIC OXIDATION

Components	Catalyst	Temperature Range, °C	Exhaust Component Removed	References
Auto Exhaust	Redox catalyst-cobaltic oxide, cupric oxide & a catalytic carrier	500°	NO_x-Reduction reaction in presence of CO. CO & HC - oxidation reaction	U.S. 3,398,101 International Copper Research Association, Inc.
Auto Exhaust	Oxidizing granular catalyst activated zeolite ore, pure manganese oxide and pure copper oxide	200-300°	CO	U.S. 3,436,356
Auto Exhaust	Copper oxide and palladium on a support of alumina & clay	260-927°	CO and HC	U.S. 3,428,573 Ethyl Corporation New York
Auto Exhaust	Alumina supported metal oxides	300°	HC and CO	U.S. 3,493,325 Monsanto Co. St. Louis, Mo.
Auto Exhaust	Platinum on a high surface alumina particle	213°	HC and CO	U.S. 3,458,276 Universal Oil Products Co.

TABLE 19, continued

REMOVAL PROCESS SUMMARY
CATALYTIC OXIDATION

Components	Catalyst	Temperature Range, °C	Exhaust Component Removed	References
Auto Exhaust	Alumina impregnated with copper oxide and palladium	350-450°	HC and CO	U.S. 3,485,593 Ethyl Corporation New York
Auto Exhaust	Manganese & chromium oxides on alumina	350-450°	HC and CO	U.S. 3,272,759 E. I. DuPont
Auto Exhaust	Two-stage oxidation and reduction beds	500°	HC, CO and NO_x	U.S. 3,429,656 Esso Research

oxidation temperatures well in excess of 100°C and 100% efficiency levels over 200°C. It should be noted here that one of the criterion for automotive catalytic muffler use - retention of catalytic activity at elevated temperatures - is not relevant to continuous ambient-temperature operation on tunnel ventilation gas. Thus, while the manganese-copper oxide combinations were downgraded by Cannon and Welling because of high-temperature loss of activity, the ability of these catalysts to oxidize both CO and unburned hydrocarbons at room temperature in the presence of water vapor is extremely significant in terms of the objectives of the tunnel ventilation program, and high-temperature structural and activity changes are not pertinent. Because of this change in criteria of acceptability, prior work on the catalytic oxidation of automotive exhaust fumes has to be re-examined or repeated.

The usual low-temperature CO catalysts such as hopcalite, are susceptible to poisoning with water vapor. It is believed that a part of this water-caused loss in activity may be due to capillary condensation and blockage of pore flow at low temperatures, which phenomenon would also be expected to be operative on any fine-pore, high-area catalyst. However, Sutt[59] reported two new catalysts support on activated-carbon which were claimed to be resistant to water-vapor poisoning. Of the two catalysts tested, a copper II chloride/platinum group combination on carbon was found to be functional for CO oxidation at lower temperatures (25°C) than a transition-metal oxide catalyst (150°C). When tested on ammonia synthesis gas at 25°C at a space velocity of 200, the Cu/Pt/carbon catalyst gave 100% CO oxidation at a CO selectivity (in the presence of H_2) varying from 0.86 to 1.0. Because the syngas used has a relative humidity of 80%, excellent resistance to water poisoning is indicated, although confirmation of this behavior at higher space velocities would be desirable.

In 1964, the state of California certified a number of catalytic muffler systems as being capable of meeting their projected 1966 emission standards of 275 ppm hydrocarbons and 1.5% carbon monoxide, averaged over 12,000 miles. However, the automobile manufacturers chose to meet the emission standards by air injection into the exhaust manifold (manual transmissions) or by modification of the fuel-air ratio, spark timing and other aspects of engine design. As a result, none of the catalytic devices were ever used, and further research on these reactors virtually ceased in 1964. The ultimate capabilities of catalytic mufflers are the subject of some speculation, but there is evidence that they can meet the more stringent emission standards projected for the mid- and late-1970's. Improve-

ments are required to meet the disadvantages shown in the 1964 test campaign:

a. Short life-time of 6,000 to 12,000 miles.
b. Susceptibility to lead and particulate poisoning (a contributing factor to the short life).
c. Susceptibility to inactivation by temperatures in excess of 1700°F, a level occasionally reached in the exhaust.
d. Relatively high initial cost of $75 to $100, with frequent maintenance and replacement costs.

One of the primary causes of short catalyst life in the 1964 California tests was the coating of the catalyst surface with lead[60]. The use of a non-leaded gasoline would obviously remove this cause of failure, and also would yield a smaller and less-sluggish converter. With the advent of increasing supplies of unleaded gasolines, exhaust catalysts have been classified according to applicability to leaded or unleaded (poisoning or non-poisoning) gasolines[61]. However, the other de-activation mechanism of over-heating would still remain. For these reasons, it has been stated by the American Chemical Society that "difficulties thus remain in the development of a catalytic converter that could meet even the 1968 or 1970 federal standards for hydrocarbons and carbon monoxide at reasonable cost and with reasonable lifetime [62].

The outlook for the possible use of catalytic oxidation techniques for the removal of CO and unburned hydrocarbons at the conditions specific to projected tunnel gas application is not encouraging. There are no known instances of industrial application of catalytic oxidation at the large gas flow volumes, low combustible concentration, and most important, at the relatively low temperatures involved in tunnel air treatment. More to the point, there are no known successful industrial installations involving any one of the three specific parameters stipulated. Although the new low-temperature catalyst laboratory data reviewed above appears hopeful particularly for CO oxidation, a great deal of additional development work is obviously required for the full evaluation of the large-scale utilization of such technology. Feasibility determination requires further information on allowable space velocity, possible trace metal poisoning, catalyst life, costs and availability, and the present laboratory data fall short of these assessment requirements. Again, the practicality of trying to accomplish at ambient tunnel conditions what has not been commercially accomplished at the more favorable concentration and temperature conditions prevalent in the source exhaust, must be

seriously questioned. Should low-temperature oxidation of the major pollutant, CO, prove feasible, then a secondary operation, such as adsorption, will be required for removal of the hydrocarbon content. Such dual processing is certain to be costly, even if probably feasible.

It should be noted that industrial application of catalytic oxidation has not been found acceptable for hydrocarbon oxidation use in the Los Angeles area[63]. In reviewing the use of catalytic afterburners for solvent emission control, Krenz stated that permits are no longer being issued by the Los Angeles County APCD for these units because "source test data indicate that these catalytic afterburners could not meet the 90 percent efficiency requirement of Rule 66". There are other, and conflicting, reports in the literature on the success of commercial installations of catalytic oxidation units. For example, the successful use of a CAB on an acrylic monomer vapor in several different units at Johnson Wax Company plants has been reported[64]. Conversely, only partial oxidation of a mineral solvent fume was obtained at a GAF Corporation vinyl floor covering plant with CAB, and this process was abandoned in favor of a condensation-mist eliminator system[65].

Information privately available to PDA on catalytic oxidation uses indicates that CAB is highly effective for situations where the material to be oxidized is either a single component or an homologous group of compounds. Further, for an efficient design, the concentrations and exhaust conditions must be known in detail. For most applications involving a wide range of combustible materials at variable concentrations, CAB will not yield adequate efficiency levels.

Thermal Afterburning

All of the development work on thermal afterburning of the residual CO and hydrocarbons in vehicle exhaust has been done as source control work.

Early efforts to complete the combustion of the unburned hydrocarbons and CO leaving the cylinders involved both air injection into the exhaust manifold and direct flame afterburners[42]. Air injection and/or engine design changes appear to be sufficient to meet the 1970 federal standards for CO and hydrocarbon emissions, but for the projected lower emission levels, more advanced systems are required. One such system under active development is the exhaust manifold thermal reactor, a unit which has been extensively developed by DuPont[66][67]. Exhaust reactors

are suitable for use with leaded gasolines, and their use would permit continuation of present gasoline formulations. The exhaust manifold reactors mount on the engine in place of the conventional exhaust manifolds. Air is injected into the exhaust ports, using the air injection system now standard on most production autos. The reactor consists essentially of an initial mixing chamber, followed by baffled passageways to provide adequate retention time at high temperature. The DuPont units use concentric annular baffles surrounding the central mixing tube. Development efforts have been directed at finding suitable low-cost materials that will endure the 1700°F reaction temperatures, and also have adequate erosion resistance to the high-velocity lead compounds impinging with the exhaust.

In an initial 100,000 mile test, an early DuPont Type I reactor[66] held average emissions to 27 ppm hydrocarbons and 0.65% CO, but suffered from baffle erosion. An improved later version, Type V, was claimed[67] to yield emission levels of 0.2 g/mile HC and 4.5 g/mile CO, both well below the 1974 California standards.

Thermal incineration of small quantities of combustibles in air requires temperatures of the order of 1100°-1500°F. Because of the virtually trace quantities of oxidizable material, none of the heat requirements can be internally derived, and must therefore be completely supplied externally. Even where a fraction of the thermal energy was internally derived, the economic penalty attached to the higher temperatures of direct incineration was calculated by Hein[68] to be from 150 to 600% of the cost of an equivalent catalytic oxidation temperatures of 500° to 800°F lower than for thermal incineration. The external fuel and cooling costs for thermal cycles of the order of magnitude required for direct incineration of the CO and HC in the bulk tunnel air thus appears to be insupportable.

Adsorption

Selective removal of hydrocarbons from a gas stream can be effected by the process of physical adsorption. Although activated carbon is the usual sorbent employed for the vapor-phase adsorption of organic molecules, other high-surface area media, such as synthetic zeolites, silica gel and alumina, have been used for selective removal of organic and inorganic contaminants. The synthetic zeolites generally have better sorption efficiencies than the carbons[43] but they do not have as great an equilibrium-holding capacity. They are therefore occasionally used as the final cleanup bed in a two-adsorbent system to remove the last traces of pollutant.

Activated carbon is the sorbent of general industrial use, and this material will adsorb, by means of Van der Waal's forces, all components from air with molecular weights greater than N_2 or O_2. The term "carbon", is something of a misnomer, inasmuch as activated carbon contains 2 to 25% oxygen and considerable quantities of hydrogen[69]. Activated carbon may be more properly viewed as a complex organic polymer with a large internal surface. A fairly voluminous literature on activated carbon exists. Hassler[70] presents a detailed review of the prior literature, history, and current applications in his book, while some preliminary engineering design theory and practice is covered in two standard references[71][72]. Barry[73], after reviewing published information, concluded that adequate design and process scaleup procedures were not satisfactory at that time. Confirming this finding, the Los Angeles County APCD and the U. S. Public Health Service undertook the evaluation of sorption design methods and obtained and published updated design data[74]. Nevertheless, valid design requires reliable laboratory data for the specific organic or organic mix, a requirement seldom satisfied in advance.

Vapor-phase adsorption over activated carbon is a gas-solid equilibrium process where the rate of adsorption is proportional to the displacement from equilibrium (driving force). The equilibrium driving force is favored by low temperatures and high pressure, and in many cases, by smaller carbon particle sizes. Because activated carbon costs are in the range of $0.75/lb, adsorption beds are normally regenerated with steam or hot inert gas to permit re-use. Physical adsorption is an exothermic operation and heat must be supplied in regeneration to overcome the energy of adsorption. Steam is a convenient source of thermal energy and because of its low (ambient) vapor pressure and condensability, it is the regenerant of choice. However, the normal temperature range of saturated steam is not sufficiently high to completely strip an adsorbed phase from the carbon, and steam-regenerated carbon cannot normally be employed for very low concentrations of organic pollutants. For example, Mattia[56] states that 3.5 lbs of steam/lb of stripped organic is required when the vapor-containing air in the sorption cycle is 0.2%, while over 30 lb of steam/lb of organic may be required when the pollutant concentration level is reduced to 200 ppm.

Adsorption techniques have been applied to the control of evaporative emissions from automobile fuel tanks and carburetors. Vapor-capture systems, employing activated-carbon canisters or foamed polyurethane, serve as storage systems for the vapors released during engine shutdown. The

stored vapors are purged from the sorbent on engine startup into the intake system of the engine[75]. The main problem with such adsorption/desorption systems had been the upsetting of carburetion by over-enrichment of the engine feed on startup, but automatic valve control appears to have solved this particular problem. The technical feasibility of such evaporative control systems has been demonstrated[42] and it is expected that they will be incorporated in 1972 production models.

The use of activated carbon adsorption for the continuous removal of hydrocarbons from tunnel air appears to be technically feasible, inasmuch as this is normally an ambient temperature operation. In terms of the tunnel ventilation problem, activated carbon adsorption has potential only with respect to the organic content of the gas, although in combination with other sorbents, it may also partially cover NO_x. It will be deficient with respect to CO removal, the major constituent of the pollutant input, and can therefore be considered as only a partial or supplementary control process for this application. The major objection to activated carbon treatment of large flows of gas typical of the projected tunnel application is one of capital cost. Exclusive of erection costs, total installed costs for carbon sorption systems using steam regeneration, are estimated to be $32.50/lb of contaminant capacity per cycle[43]. Operating costs depend on the frequency and length of regeneration life of bed, contaminant concentration level, and necessity for pre-filtration and second-sorbent systems. Given the very dilute organic contaminant level in tunnel air and the nature of the pollutant mix, activated carbon sorption may have to be supplemented with a cleanup operation employing a different sorbent, thus compounding the cost problem.

To meet some of the cost objections to carbon sorption systems as applied to low concentration level systems (200 ppm), Mattia[56] proposed the "Zorbcin" process, in which the stripped organic obtained during regeneration is incinerated to provide both the heat and inert gas needed for regeneration. In the event that organic recovery rather than incineration is indicated, Mattia proposed a "Cascade" operation in which a pair of primary adsorbers in parallel feed a single secondary adsorber. An economic comparison of various modes of sorption and/or incineration systems indicate that the "Cascade" arrangement had the lowest annualized cost, including an appreciable credit for the recovered solvent. Without this recovered solvent credit, the "Zorbcin" arrangement was the most economic. However, if a low-concentration and ambient-temperature catalytic oxidation technique is available, there

would be no point to sorbing organic pollutants prior to an elution and burning sequence.

The presence of particulates in an air stream being processed by activated carbon sorption poses several problems. If the particulates are solid, then the carbon bed may act as a filter and the flow resistance of the unit will increase or it may plug. Very fine solids or aerosols may also poison the sorption abilities of the carbon, and a sorption bed must usually be protected from particulate effects by suitable pre-filtration means. If the aerosol size and bed depth is such that bed penetration occurs, then aerosol buildup in the gas will occur in a recycle system, unless an efficient particulate collection technique such as electrostatic precipitation or filtration is used in series with the adsorption unit.

Carbon adsorption is usually carried out in fixed-bed units, although fluidized beds and moving bed devices such as rotating drum contactors have seen limited industrial use[41]. Various fixed-bed arrangements of sorption beds, such as by-pass and panel beds, have been devised[70] in order to reduce the flow resistance by increasing the flow area per unit bed weight. In this regard, some of the newer panel filter bed designs being developed for the simultaneous removal of SO_2 and fly ash from flue gas[76] are of interest, and may be adapted for carbon bed application.

Wet Scrubbing

"Wet scrubbing" in the field of pollution control has two different meanings. It is applied to both particulate removal and gas absorption, and despite the disparity of function, distinction between the two application areas and types of equipment is sometimes not made. A case in point is Table 20 taken from a recent review. Of the eight types of equipment listed, only two, the packed and spray towers, are conventional mass transfer or gas-absorption devices. As is obvious from the particulate-removal efficiencies for these two types of equipment listed in Table 20, they, as well as the primarily dust-scrubber units, have some degree of dual-functionality. However, for mass transfer contactors, dust collection is usually incidental and vice versa, and because of the extreme differences in design theory and objectives, separation by primary function is desirable.

Absorption methods for the removal of a specific gaseous pollutant by dissolution in selected solvents constitute the oldest, most versatile, and varied gas-scrubbing operations. While gas absorption technology has attained

TABLE 20

SCRUBBER CAPABILITIES (IMPERATO)

Type of Scrubber	Usual Range of Particle Sizes, Microns	Normal Draft Loss, In. Water	Maximum Efficiency, %	Typical Applications
Open spray tower	10.0	3/4-2	85	Iron pyrite roasting
Packed tower	10.0	1-6	85	Absorption of fluorine compounds
Wet centrifugal	2.5	2-6	95	Phosphate dust from fertilizer plants
Flooded bed	2.5	2-8	95	Primary washer for blast furnace gas
Orifice	2.5	To 6	95	Rock and cement dust
Wet dynamic	2.0	None	98	Heavy concentration of fine particles
Venturi	0.5	6-80	99+	Oxygen converter & ferrous cupola gas, acid mist, lime dust, coal dust, incinerators
Flooded disk	0.5	6-70	99+	Same as for venturi

a high degree of industrial utilization and dependability, attempts to apply this technology to pollution control problems have been tentative and not entirely successful. The major obstacles to fuller use of existing absorption techniques in the pollution control area are: (a) lack of equilibrium data at trace contaminant levels, which is primarily an analytical measurement problem, (b) lack of efficiency design data in these new regions of concentration, and (c) lack of reliable industrial application experience in this area.

The primary function of any piece of absorption equipment is to provide a large active area of contact between the gas and liquid phases. This is accomplished by dispersing the liquid phase over a geometric packing material or as droplets by spraying.

Packed tower absorbers may be used in three modes of two-phase flow operation: (a) countercurrent, (b) cocurrent and (c) crossflow. The maximum degree of absorption efficiency (most number of transfer units, or NTU) is obtained with countercurrent contact, and for difficultly-soluble gases, or maximum degree of removal, this is the preferred type of contact unit. In an absorber, the completeness of solute removal from the gas stream is a sensitive function of the time of contact or height. Because the gas pressure loss through the packing is directly proportional to the height of packing, this latter factor controls efficiency and affects gas blowing costs. For this reason, a large variety of low-loss, high-efficiency packings have been developed commercially. Because any packing shape represents a compromise between the conflicting requirements of high fluid dispersion and low gas pressure losses, each tower packing has its particular optimum area of application.

The key engineering estimate in packing selection and column design is assessment of the required volume of packing for a given amount of transfer. To make this estimate, some type of packing performance index, in the form of either a volumetric coefficient, $K_g a$, or height of a transfer unit, (HTU), must be employed. Despite the rapid advances in fundamental transfer theory in recent years, the body of design information available to the engineer has not reflected these advances. The difficulty is that, even for a given system and packing, the coefficients are not invariant properties, but depend on flow rates and operative portion of the equilibrium curve. The standard procedure is therefore to select design performance data whose conditions or determination most closely approximate those of the application. For trace contaminant removal this information is unavailable.

Spray chambers or towers may be used for gas absorption in cases where only a few transfer units are required, i.e., for soluble gas components. These units have the advantages of very low gas-phase pressure drop and inexpensive construction, but do not offer countercurrent contact. Four types of spray systems are used commercially: (a) simple spray columns, (b) cyclonic spray towers, (c) venturi scrubbers, and (d) jet scrubbers. The spray chamber is a contacting device that is frequently used in situations where a contaminated gas stream contains both particulates and a highly soluble gas component. Particle collection in spray towers is discussed below, but the mass transfer characteristics of this equipment is pertinent to the removal of the oxygenated, partially-oxidized, hydrocarbons in the exhaust. These include such components as acrolein and formaldehyde, which are objectionable from the point of view of odor and irritation effects.

Spray scrubbers can remove hydrocarbons from a gas stream by three mechanisms[79]: (a) dissolution of the vapor component in the liquid, (b) condensation by temperature differential, in the same manner that air is dehumidified by cold water sprays, and (c) vapor molecules may adsorb on particulate matter which is subsequently removed by impingement on the liquid drops. Design data are available primarily for the solubility mechanism, and a fully valid design would undoubtedly require preliminary test data. With respect to the solubility mechanism, literature data for spray towers[80] showed that the number of transfer units was proportional to the liquid rate, and was increased by a finer spray (higher liquid power input). The rate of mass transfer was most rapid near the spray nozzle, owing to the formation of fresh liquid surface and collection of spray by the chamber walls. Entrainment is a problem with spray tower use, particularly at the higher gas flows, although this problem may be resolved by the use of suitable mist eliminators or cyclonic flow spray towers.

Application of wet scrubbing gas absorption techniques to removal of contaminants from tunnel ventilation air poses several problems. If an organic solvent is employed as a solvent, even if a high-molecular weight material is employed, its vapor pressure will unavoidably be at least the same order of magnitude as some of the pollutants, so that the net effect could be substitution of one pollutant, the solvent, for another, the solute. A similar problem exists with water as a solvent, since recycle of gas through an aqueous phase system will tend to adiabatically saturate the air. Continuous operation of a tunnel at 100% relative humidity is not desirable, and application of wet scrubbing

techniques would require the use of a downstream condensing system to remove solvent vapors. If the absorber is operated at ambient temperatures, then the downstream solvent-removal condenser must be operated at low, or refrigerant, temperatures in order to remove solvent. This, in turn, means that the bulk tunnel air must be thermally cycled between refrigerant and ambient temperatures, adding a thermal cooling and heating cost to the base operation of the absorption.

It appears that the humidification or saturation problem will probably prevent in situ tunnel application of absorption processes. However, the possibility remains of using such a process on the exhaust air from the tunnel. While the washed air may generate a steam plume under certain atmospheric conditions, exhaust processing would prevent local accumulations of pollutants, and the possibility of contaminant recycle in situations where the intake fan is located near the exhaust fan. A number of tunnels already have spray chambers installed to protect the exhaust fans in the event of tunnel fires, and their use as exhaust control devices would represent only an operating cost increment. While the disposal of the polluted water resulting from wet scrubbing may be a problem, this can be minimized by the use of water recycle operation, with a small amount of make-up and bleed liquid. The recycle mode of operation would also permit use of exhaust wet scrubbing in tunnels without ready access to large amounts of water.

Nitrogen Oxides

Combustion of a hydrocarbon fuel with air normally results in the combination of part of the nitrogen and oxygen to form nitric oxide (NO) at the higher temperatures. Subsequent to its formation, NO is oxidized by residual or atmospheric oxygen to nitrogen dioxide, NO_2:

$$2NO + O_2 = 2NO_2 \qquad (13)$$

The oxidation of nitric oxide is a slow exothermic reaction, liberating 24,250 Btu/lb mole, and is favored by low temperatures. The oxidation reaction in air is markedly concentration-dependent. When the original concentration of NO is 2% by volume, it requires 10 seconds for half the NO to oxidize, while it takes nearly 60 hours for a similar degree of oxidation when the initial NO concentration is 1 ppm[81]. Kinetically, the oxidation reaction is third-order, and the rate constants have been thoroughly explored by Rao[82] for the homogeneous gas-phase reaction. This latter investigation also explored the catalyzed oxidation of nitric oxide, using both activated carbon and silica gel as catalysts.

The variable mixture of NO and NO_2 (plus minor amounts of other nitrogen oxides) is commonly designated as NO_x. NO_x formation is favored by high combustion temperatures and excess oxygen, so that for internal combustion engines, the highest emissions are associated with air-fuel ratios slightly on the lean side of stoichiometric. High speeds and heavy accelerations produce the major portion of the NO_x, and levels of NO_x emissions in typical urban traffic range between 800 and 3000 ppm[42]. Data published by the Los Angeles County Air Pollution Control District, as presented by Faith[83] and given in Table 21 show the effect of driving variations on NO_x emissions.

Nitrogen tetraoxide (N_2O_4), the dimer of NO_2, is not considered to be a significant component of NO_x, because equilibrium considerations show that virtually complete dissociation to NO_2 will occur at 100 ppm dilution in air[79]. Although NO_2 is soluble in water, NO is only sparingly soluble. However, the difficulty in attempting to remove NO_2 by water dissolution at concentrations greater than a few ppm is that the reaction with water produces NO:

$$3\ NO_2 + H_2O = 2HNO_3 + NO\ (K = 2 \times 10^8) \quad (14)$$

At very low concentrations of NO_2, the reaction with water is:

$$2\ NO_2 + H_2O = HNO_2 + HNO_3\ (K = 10^5) \quad (15)$$

and in warm water, the HNO_2 is unstable:

$$3\ HNO_2 = HNO_3 + 2NO + H_2O \quad (16)$$

The NO released in any of the above dissolution reactions must be re-oxidized to NO_2.

Nitrogen dioxide is a strong absorber of ultraviolet light and is the initiator compound for the chain reactions resulting in the formation of ozone and photochemical smog. A simplified reaction scheme for the formation of photochemical smog[62] indicating the trigger role of NO_2, is given in Table 22. The first two reactions show the probable primary oxidant (ozone) formation mechanism, while the subsequent reactions indicate the formation of secondary irritants and pollutants. A few tenths of a ppm of NO_x and less than 1 ppm of reactive hydrocarbons (unsaturated) are sufficient to initiate the reaction chain, but values as high as 0.7 ppm NO_x and 3 ppm hydrocarbons have been found for ambient atmosphere on smoggy days. Although ultraviolet radiation is not available in vehicular tunnels, Faith[83] states that experience in the gas industry shows that oxides of nitrogen in extremely small

TABLE 21

RESULTS OF A TYPICAL ANALYSIS OF AUTOMOBILE EXHAUST GASES

	Idling	Acceleration	Cruising	Deceleration
Hydrocarbons (C_3-C_9), as hexane, ppm...	1275	410	354	5125
Acetylenic, as acetylene, ppm.....	825	18	64	687
Oxides of nitrogen, as NO_2, ppm.....	8	4180	1606	18
Lower aldehydes, as formaldehyde, ppm..	88	1369	264	193
CO %.....	3.6	0.0	0.4	1.5
CO_2 %.....	10.0	13.7	12.9	6.1
O_2 %.....	1.4	1.3	1.1	9.5

Data published by Los Angeles County Air Pollution Control District

Faith, W.L., Chem. Eng. Progr. 52, p 342, 1956.

TABLE 22

SIMPLIFIED REACTION SCHEME FOR PHOTOCHEMICAL SMOG

NO_2 Nitrogen dioxide	+	Light	⟶	NO Nitric oxide	+	O Atomic oxygen
O	+	O_2 Molecular oxygen	⟶	O_3 Ozone		
O_3	+	NO	⟶	NO_2	+	O_2
O	+	Hc Hydrocarbon	⟶	HcO Radical		
HcO	+	O_2	⟶	HcO_3 Radical		
HcO_3	+	Hc	⟶	Aldehydes, ketones, etc.		
HcO_3	+	NO	⟶	HcO_2 Radical		
HcO_3	+	O_2	⟶	O_3	+	HcO_2
HcO_x Radical	+	NO_2	⟶	Peroxyacyl nitrates		

This reaction scheme is intended to be illustrative, not definitive. Research is still in progress on the detailed chemistry of the smog-forming process.

quantities will react with hydrocarbons to form particulate matter, even in the dark. This latter role of NO_x with respect to in situ particulate matter generation in tunnels has apparently not been investigated, so that based on present data on concentration levels, the primary objection to tunnel NO_x concentrations would be with respect to exhaust to the ambient atmosphere.

Source Control

It was recently announced[84] that the Environmental Protection Agency has proposed a 3 gram per mile standard for nitrogen oxide emission limits for 1973 model vehicles. It was noted that the existing California standards for 1971 vehicles is now at a 4 g/mile NO_x limitation, as against a proposed California limit for 1974 of 3 g/mile. Additionally, the California limits on NO_x emissions dropped to 1.3 g/mile for 1974 vehicles and 1.0 g/mile for 1975 vehicles. If these latter limitations are followed by EPA this would call for emission reduction of 75% in NO_x over present 1971 standards.

Design changes made on internal-combustion engines for the purpose of reducing the emission of unburned hydrocarbons and carbon monoxide through more efficient combustion generally have the opposite effect on nitrogen oxide production. The higher combustion temperatures and excess oxygen attendant on more efficient combustion or secondary oxidation are exactly the conditions serving to increase the degree of nitrogen fixation. Conversely, reduction of the combustion temperature and the amount of oxygen available at this temperature serves to reduce the NO_x levels, and this provides the basis for the most common approach to control: exhaust gas recirculation.

The exhaust gas recirculation system developed by Esso Research and Engineering Company[85] utilizes a system which recycles gas from the exhaust throttle plate. A simple vacuum-operated on-off valve shuts off the recirculation at idle to give smooth engine operation and also at wide-open throttle to prevent loss in vehicle performance. Dynamometer tests for 50,000 miles at a recirculation rate of about 15 percent showed consistent reduction of NO_x levels to the 1974 California standards of 1.3 grams of NO_x per mile. Theoretically, 90 percent NO_x reduction will require 30 percent exhaust gas recycle levels[42] but the decrease in power generation at this recycle level may not be acceptable.

NO_x emissions from vehicles can also be controlled by catalytic reduction in the exhaust stream. However, such

a reduction operation requires the presence of a reducing gas such as CO or a hydrocarbon, and this is obviously inconsistent with other exhaust control objectives. For this reason, most proposed catalytic muffler systems for control of NO_x call for two separate reactors or catalyst beds, one operating at reducing conditions for NO_x reduction, and the other at oxidizing conditions for CO and HC removal. A case in point is presented by Taylor, 1969, in U. S. Patent No. 3,429,656, assigned to Esso Research and Engineering Company[86]. Taylor's two-stage exhaust treatment calls for a primary oxidation bed to remove O_2, followed by a reducing bed containing a steam-reforming catalyst to react CO and the hydrocarbons with H_2O to form CO_2 and H_2, and reaction of the NO_x with the hydrogen thus produced.

A recent news announcement[87] disclosed the development of a new "nickel-copper" catalyst claimed to be 90% effective for NO_x reduction in automotive exhaust. It was also indicated that the new catalyst for NO_x removal would be part of a dual-catalyst system, with the second catalyst capable of oxidative removal of CO and hydrocarbons. However, the development of exhaust catalytic converters for NO_x does not appear to have progressed to the same feasibility point as the exhaust recycle units.

Hardison[88] and Fletcher[89] have reviewed both elevated and atmospheric pressure catalytic processes for the reduction of NO_x in the tail gases from industrial nitric acid plants. When the emission limit is of the order of 200 ppm European practice is to use a two-stage reduction system. The first stage is used to remove practically all of the oxygen from the gas stream to secure the necessary complete reduction in the second stage. Operating temperature limits are from 900° to 1400°F, and this type of reduction operation does not appear to be feasible for the tunnel ventilation problem, because of both the temperature level and the oxygen-removal feature. The normal atmospheric concentration of oxygen in tunnel recycle air, and the obvious necessity of maintaining this level, precludes the use of any reductive catalytic technique which could consume oxygen. Thus, the only potential for catalytic reduction application to NO_x has to stem from the possibility of selective reaction with a reducing agent such as CO in the presence of O_2. This latter reaction has been studied by both Baker[90] and Ryason[91], at the laboratory level.

It is anticipated that removal of nitrogen oxides from tunnel air by any conventional technique, including catalytic reduction may be the most difficult objective to achieve. Thermodynamically, the decomposition of NO into

O_2 and N_2 is quite favorable, but no catalyst has been found that will effect this decomposition at reasonable rates or temperatures[92]. While the destructive catalytic oxidation of CO and hydrocarbons requires an excess of O_2, catalytic removal of NO_x from a gas stream normally employs reducing conditions. However, the use of two or more different catalysts with dissimilar selectivities at reaction conditions often allows the catalysis of incompatible reactions. Even in the presence of excess O_2, a catalyst with the capability of adsorbing both CO and NO_x selectively, could yield an "internal" reductive reaction. Ryason[91] studied the catalyzed reaction of NO_x with CO at high space velocities and temperatures and found alumina-supported catalysts to be effective. However, temperatures of 1000°F were required, plus stoichiometric quantities of reactants, so that this approach to tunnel gas cleanup is not apparently promising.

An extremely comprehensive and detailed body of work on NO_2 adsorption was developed in connection with the Wisconsin process for the production of nitric acid[93]. This process employed shallow fluidized beds of silica gel for the adsorption of NO_2, and this process was demonstrated on an industrial scale. Silica gel contacting was also used in this process for the catalytic oxidation of NO to NO_2. The published data on this silica-gel-based oxidation-sorption operation show the following specific points:

a. Sorber design was based on operation at 10°F at a gel: NO_2 ratio of 14. Poor recovery was indicated at temperatures above 10°, regardless of gel flow.
b. Catalysis of NO oxidation to NO_2 by silica gel required a gas dewpoint of -60°F.

It is obvious that both of the above specifications are outside the range of probable tunnel application with respect to utilization of ambient temperatures and in-tunnel dewpoints. The sorption concept is nevertheless of continuing interest; Sundaresan[94] reported that a commercial zeolite (molecular sieve) was more efficient than silica gel for removing very low concentrations of NO_x from a nitric acid plant tail gas. NO_x selectivity in the presence of organic contaminants has not been explored for zeolite or carbon adsorption, and laboratory studies of such selectivity at the low levels of NO_x concentration indicated for tunnel air must be made before actual application can be seriously considered.

As shown above in the brief review of the dissolution reactions of NO_2, wet scrubbing of NO_x, particularly at low concentrations, is neither a straightforward nor efficient absorption situation. Further, other soluble gas components likely to be present in tunnel gas, such as CO_2 and SO_2, will interfere with NO_x solution equilibria. A detailed review of the difficulties associated with the sorption of low concentrations of NO_x from power plant stack gases has been recently published[95]. In connection with this latter review, a paper by Bartok[92] indicated that absorption (with chemical reaction) appeared to be the most promising potential technique for the removal of NO_x from power plant stack gas, and suggested the use of recycle limewater or magnesium hydroxide solution. However, the potential "promise" of this absorption technique was based on two conditions that would not necessarily be obtained in the case of tunnel ventilation:

a. Cost-benefit calculations on a complex magnesium hydroxide absorption flow sheet showed absorption to have the lowest annual costs only because by-product credits offset the high capital charges for installation.
b. It was assumed that equimolar concentrations of NO and NO_2 (N_2O_3) could be obtained in the gas in order to optimize absorption.

The assumption of equimolar NO and NO_2 gas contents finds some support in the literature; Radhakrishna[96] studied the removal of NO_x with dilute sodium, potassium and calcium hydroxide solutions, and found that when the alkali was in excess, equal amounts of nitrate and nitrite were formed. However, this may be a liquid-phase reaction, rather than a catalyzed gas-phase displacement. In any event, NO_x removal from tunnel air by wet scrubbing means apparently requires intensive development effort prior to feasibility determination, and this operation does not appear to be susceptible to design or installation at present.

Particulates

The government has estimated that current vehicles emit approximately 0.3 g/mile of particulate matter[67]. Although particulate matter has not as yet been clearly defined, and neither measuring techniques nor test cycle conditions have been specified, a standard of 0.1 g/mile has been proposed for 1975, and a 1980 level of 0.03 g/mile. According to Stern[42], automotive exhaust emissions contain 70% by count of extremely fine particles in the size range

of 0.02 to 0.06μ. However, on a mass distribution basis, particles less than 1.0μ in size account for less than 5% of the total weight of the particulate matter in the exhaust.

Exhaust particulates contain both inorganic and organic compounds of high molecular weight, with the most significant fraction consisting of lead compounds deriving from the tetraethyl lead antiknock compounds. Approximately 75% of the lead burned in the engine is exhausted to the atmosphere, with the total amount of lead particulates discharged being proportional to the concentration of tetraethyl lead in the gasoline. It is worth noting that the current introduction of low-lead and non-leaded gasolines at the fuel pumps will directly yield significant reductions in the total particulate emission.

In addition to the lead salts, the exhaust particulates may also represent carbon, iron rust, tars and oil mists. Further, tunnel air also contains particulates derived from tire abrasion, salt (from winter salting operations) and fugitive dust. The primary particulate contributor is exhaust, both from gasoline and diesel engines. The latter exhaust is particularly high in smoke and odor compounds (partially-oxidized hydrocarbons), and the use of barium-based smoke suppressant additives may give rise to a unique set of particulate emission problems[42]. Barium sulfate has low toxicity, and there is usually enough sulfur in diesel fuel to yield this innocuous compound in the exhaust ash. However, water-soluble barium salts are toxic, and complete sulfation may not always be certain.

The organic particulates, or condensates on particulates, are of major concern because of the probable presence of carcinogens, principally benzo(a)pyrene (BaP), and possibly fluoroanthrene and coronene. The extent to which these carcinogens contribute to the tunnel and outdoor concentration is shown in Table 23, representing 1961 sampling of the Sumner Tunnel in Boston. Also shown in Table 23, is the relative levels of metals in the particulates.

DuPont has developed an exhaust particulate trapping device[67] which consists of a three-step operation: partial cooling, wire-mesh agglomeration, and cyclone separation. The trapped-out particulates are stored in a portion of the cyclone box, and dual exhausts are used, with a cyclone box located in each of the two rear fender wells. An early version of the three-stage exhaust trapping system maintained lead salt emission rates at 0.1 g/mile for a

TABLE 23

SUSPENDED PARTICULATE PARAMETERS IN SUMNER TUNNEL
OUTLET AND INLET AIR, SEPT. 14-20, 1961

Type of Suspended Particulate	Concentration (Nanograms/Cu.Meter) Outlet	Inlet	Difference Outlet-Inlet	Est. Relative Importance of Motor Vehicles on Outdoor Conc. Rank
Total	588,000	104,000	484,000	8
Sulfate	29,300	22,200	7,100	15
Nitrate	2,400	3,400	-1,100	
Total Organics (benzene sol.)	225,000	11,000	214,000	5
Benzo(a)pyrene	690	2.6	687	2
Benzo(g,h,i) perylene	990	4.7	985	3
Coronene	530	1.4	529	1
Metals				
Antimony	170	153	17	18
Beryllium	4.3	4.1	0.2	20
Bismuth	5.5	4.9	0.6	17
Cadmium	38	28	10	14
Chromium	128	87	41	13
Cobalt	22	20	2	19
Copper	278	67	211	9
Iron	23,397	2,264	21,133	6
Lead	44,500	1,100	43,400	4
Nickel	112	120	-8	
Manganese	133	50	83	11
Molybdenum	60	17	43	10
Tin	154	133	21	16
Titanium	472	70	402	7
Vanadium	278	325	-47	
Zinc	2,248	1,523	725	12

64,000 mile test as against a normal emission rate of 0.2 to 0.3 g/mile. In a 26,000 mile test on an improved version of the trap system, lead salt emissions were reduced to 0.03 g/mile. Perhaps even more significant were the reductions in the BaP emission rates. At 3,000 miles, the trap system reduced BaP emissions from 66 to 24 micrograms/gallon of fuel, while at 18,000 miles traveled, the reduction was from 228 to 6 micrograms/gallon. Studies are continuing, but the last test data showed that total particulate emission could be maintained at the 0.03 to 0.04 g/mile level, with a lead salt content running from 50 to 75% of the total particulates.

The DuPont exhaust trapping system described above utilized the flow energy and high velocity inherent in automotive exhaust to agglomerate and centrifugally separate the particles from the exhaust gases. Any similar external system of particulate removal must include means for imparting the same flow energy to the total gas: exhaust plus the much larger ventilation flow. Further, while agglomeration may be easily accomplished at high particle population density, it becomes infinitely more difficult with a very disperse population density. For cyclones, therefore, dust collection efficiency decreases with decreasing dust loadings[42]. Collection efficiency for inertial separators also depends on particle size distribution, particle density and other particle properties. As pointed out above, information on the nature of particulates in gasoline and diesel engine exhaust is still sketchy, and does not yet provide the basis for proper selection of collector type. Inasmuch as cyclones and other inertial devices show high efficiencies for particles in the plus-10 micron size range, such data are of extreme preliminary importance. Further, relatively high pressure drops are required for high efficiencies, and these will be at least of the same order of magnitude as the initial tunnel ventilation system itself.

Some of the pressure drop characteristics of wet collectors, as well as the gas and liquid velocity ranges were given in Table 20. Again the humidification problems existing with any type of wet contactor mitigate against the use of an internal wet scrubber, but such units may have application to the exhaust air. Most of the wet collectors listed also have a pressure drop range that would necessitate a doubling of the fan horsepower for most existing tunnels in order to operate the scrubbing equipment. Notably, the spray chamber is the sole device with an inherent resistance less than 1 inch W.G.

Aqueous spray scrubbing is capable of a high degree of particulate removal in a well-designed unit. Hangebrauck[97]

has reported that spray scrubbing removed 98% of the benzo-(a)pyrene emission from a municipal incinerator. Similar levels of control were achieved on the polynuclear hydrocarbon emission from hot asphalt blowing plants. Because polynuclear carcinogens are associated with the particulate fraction, these data indicate excellent potential for tunnel exhaust control for the most dangerous health hazards in the emission. In addition to the organic carcinogens, wet scrubbing has capability for the removal of most oxygenated organics, which are usually water-soluble, and a portion of the NO_X.

One of the few industrial control units which appears to be readily applicable to the tunnel air control problem is the electrostatic precipitator. In mechanical collectors, such filters (baghouses) and cyclones, energy is applied to the entire gas stream. In the electrostatic precipitator, the energy used for collection is applied only to the particles. The collection process consists of charging the particulates by means of a high-voltage corona discharge and then electrostatically depositing them on a grounded collecting electrode. The electric power required to maintain the corona range from 50 to 500 watts/1000 CFM[42] and voltages of from 50,000 to 100,000 volts are required[98]. Because of the highly selective energy input mechanism, pressure loss through the electrostatic precipitators is very low, from 0.1 to 0.5 inches W.G. However, gas flow through the unit must be held to low velocities (2 to 8 ft/sec) so that these devices are usually fairly large.

In addition to the volumetric requirements, other disadvantages include high capitol costs and possible dust explosion hazards in the cases of cumbustible dusts. Efficiencies of commercial units now being sold are in excess of 99%[99] and submicron particles may be collected with almost equal facility as 100-micron particles. Factors controlling design include (a) dust resistivity (b) gas temperatures (c) flow distribution and (d) moisture content of gas. For high efficiency particle removal, the electrical resistivity should be in the range of 10^4 to 10^{10} ohm-cm; actual particle resistivity ranges from 10^{-3} to 10^{14} ohm-cm[79]. High particle resistivities can lead to collection electrode insulation by a thick particle layer and subsequent back discharge of a corona from the collecting electrode, interfering with the normal performance of the unit.

An excellent review of both design and application of electrostatic precipitators is presented in the Air Pollution Engineering Manual[41] while Walker[99], has updated the cost and efficiency data for this equipment. A simpler, and potentially cheaper form of electrostatic unit, is the

"space-charge" precipitator, described by Faith[100] and by Hanson[101]. In the space-charge precipitator, the particulates are charged by a conventional corona, and then charged droplets of liquid are introduced into the gas in the form of a spray from a charged nozzle. Particles and liquid droplets are then collected by grounded wire mesh collectors. This unit combines the best features of spray absorption with the electrostatic efficiency levels of particulate removal, while avoiding the complexity and high capital cost of conventional precipitators. Unfortunately, this type of equipment is in the devlopment stage and will require extensive work before becoming commercially available.

Tunnel Pollution Control - Feasibility and Economic Evaluation

The objective of this study was to determine the technical and economic feasibility of available processes for removing pollutants from vehicular tunnel atmospheres. The pollutants are those originating in automotive exhausts, and include CO, NO_x, unburned and partially-oxidized hydrocarbons, and particulates. Early in the program, it was realized that adaptation of existing industrial pollution control technology for processing tunnel air was only one of several possible control strategies that might be employed. The other possible strategies include auto exhaust source control and tunnel ventilation augmentation. The cost and effectiveness of these latter control strategies were explored to a degree sufficient to establish a basis for comparison for the in situ secondary pollution control approach.

The present state of the pollution control technology art potentially applicable to the tunnel problem has been covered. This section deals with the preliminary technical design and cost evaluations for selected systems. The base model used for the feasibility studies is a 1-mile long, 250,000 CFM ventilation rate tunnel.

Design and economic studies have been made of industrial pollution control processes potentially applicable to the removal of pollutants from vehicular tunnel atmospheres. In addition, a study has been made of the effect of automotive exhaust source control measures programmed to go into effect in the decade of 1970-1980, on the average CO and hydrocarbon emission, corrected for automobile population age. The results of this latter study indicate that a four-fold reduction in CO and hydrocarbon emission levels will result from presently-mandated vehicle exhaust controls, and that the tunnel pollution problem will correspondingly diminish in severity unless ambient standards are changed. At minimum, it appears that tunnel ventilation design must make allowance

for the transient nature of the pollutant loadings, and at maximum, there is a good possibility that source control will eliminate the tunnel atmosphere problem.

A comparative feasibility and economic study of tunnel ventilation blower augmentation vs. various secondary pollution control processes has shown that blower addition or revision is the most technically and economically feasible route to alleviating the tunnel atmosphere pollution burden at this time. Of all of the control operations, that of catalytic oxidation, utilizing a 60% MnO_2/40% CuO ambient-temperature catalyst, appears most promising for in situ tunnel use. However, design was extrapolated from laboratory data, and further direct development work is required and recommended. From a technical viewpoint, there are serious operability questions for catalytic oxidation, activated carbon adsorption and electrostatic precipitation because the pollutant or particulate concentration in each case is well below the lower limit of any known industrial application. Economically, only catalytic oxidation appears to be near-competitive with augmented blower capacity. Spray scrubbing was assessed as a potential exhaust treatment method for control of the gross tunnel emission, and was found to be technically feasible and economically promising, although direct test verification is desirable.

A short study of recycle air operations around the tunnel or tunnel section was made, and it was found that any degree of recycle would give rise to an increase in tunnel pollutant concentration above the level obtained in once-through air operation.

The detailed review of the state-of-the-art for both source control and tunnel ventilation air treatment technology yields a number of significant conclusions which bear directly on the technology feasibility determination. In summary:

1. Control technology available for the removal of vehicle-derived pollutants comprises two distinct categories:

   (a) Source control technology already developed for removal of pollutants from automotive exhaust at exhaust conditions.
   (b) Industrial technology which must be adapted or extrapolated to tunnel air pollutants and concentration levels, as well as to ambient temperature operating conditions.

2. Vehicular pollutant source controls are already partially in operation and an escalating degree of application and efficiency is now mandated by law for the immediate five-year period. Some proven control equipment meeting proposed future emission standards already exists, and a choice of competitive techniques will apparently become available in the near future. Significant decreases in vehicular emissions have already occurred.

3. In most cases, the adaptation of conventional industrial control technology to the tunnel air treatment will require experimental development and field tests. This required preliminary work has not been done, and no present tunnel treatment installations exist.

4. As is the case with source exhaust control technology, multiple controls and processes will be required to treat the exhaust pollutant mix of particulates, NO_x, hydrocarbons, oxidized hydrocarbons and CO in tunnel air. Such exhaust mixtures are more complex, varied and most important, much more dilute than those encountered in most industrial emission applications.

5. It does not appear reasonable to expect exhaust control techniques developed to operate at the high-temperature, high-pollutant concentration exhaust conditions to function at the 150-fold dilution, ambient-temperature tunnel air conditions. In pollution control design a prime rule is to treat at the point of maximum concentration prior to dilution - a rule based on both economic and efficiency considerations, as well as functional feasibility.

The above preliminary conclusions strongly indicate that tunnel air treatment is not likely to prove to be a tenable control strategy at this time, should alternate means of control be available. On the other hand there are a few standard technologies such as electrostatic precipitation, which appears to be more suitable for tunnel air processing than for source control

application. This section will be concerned with the evaluation of the capabilities of all potentially applicable technology in the context of available alternates and the changing nature of the source emissions.

Tunnel Pollution Control Strategies

The application of pollution control equipment for the removal of pollutants from tunnel air is only one of several control approaches open, and it is necessary to consider these alternates, if only from the point of technical and economic perspective. There are four apparent tunnel pollution control strategies:

A. Control of traffic loadings and speed within tunnel.
B. Increased ventilation rates.
C. Exhaust source controls.
D. Tunnel air treatment.

Pragmatically, the first two control strategies are standard present control modes for tunnel pollution problems, although recent studies[18] indicate that these techniques are not yet fully realized.

Several of the newer European tunnels, such as the Mont Blanc Tunnel and Great St. Bernhard Tunnel, opened in the 1960's, utilize traffic flow control as a means of limiting in-tunnel emissions[20]. The Mont Blanc Tunnel utilizes a system of control lights for vehicles in and entering the tunnel to control speed between 25 and 37 mph. The Great St. Bernhard Tunnel uses traffic counters to continuously monitor the number of vehicles in the tunnel, and entering traffic is stopped when the maximum number of vehicles is reached. While these are non-urban tunnels, the Lincoln Tunnel under the Hudson River, is reported[18] to be installing traffic flow controls utilizing traffic counters tied into a computer which will in turn control traffic signals. The objective is to simultaneously reduce the number of vehicles in the tunnel at any one time by increasing the average vehicular speed in the tunnel. Figure 29, taken from Ott[102] shows the reduction in CO emission with increase in average vehicle speed and it is apparent that increasing average vehicle speed is a direct CO control measure.

Information supplied by Kyle[18] on the Sumner Tunnel in Boston Harbor showed that the total longitudinal air speed in the tunnel was 14.7 mph, of which the ventilation air speed constituted only 1.3 mph, while the vehicle sweep effect contributed 13.4 mph. It should be noted that the

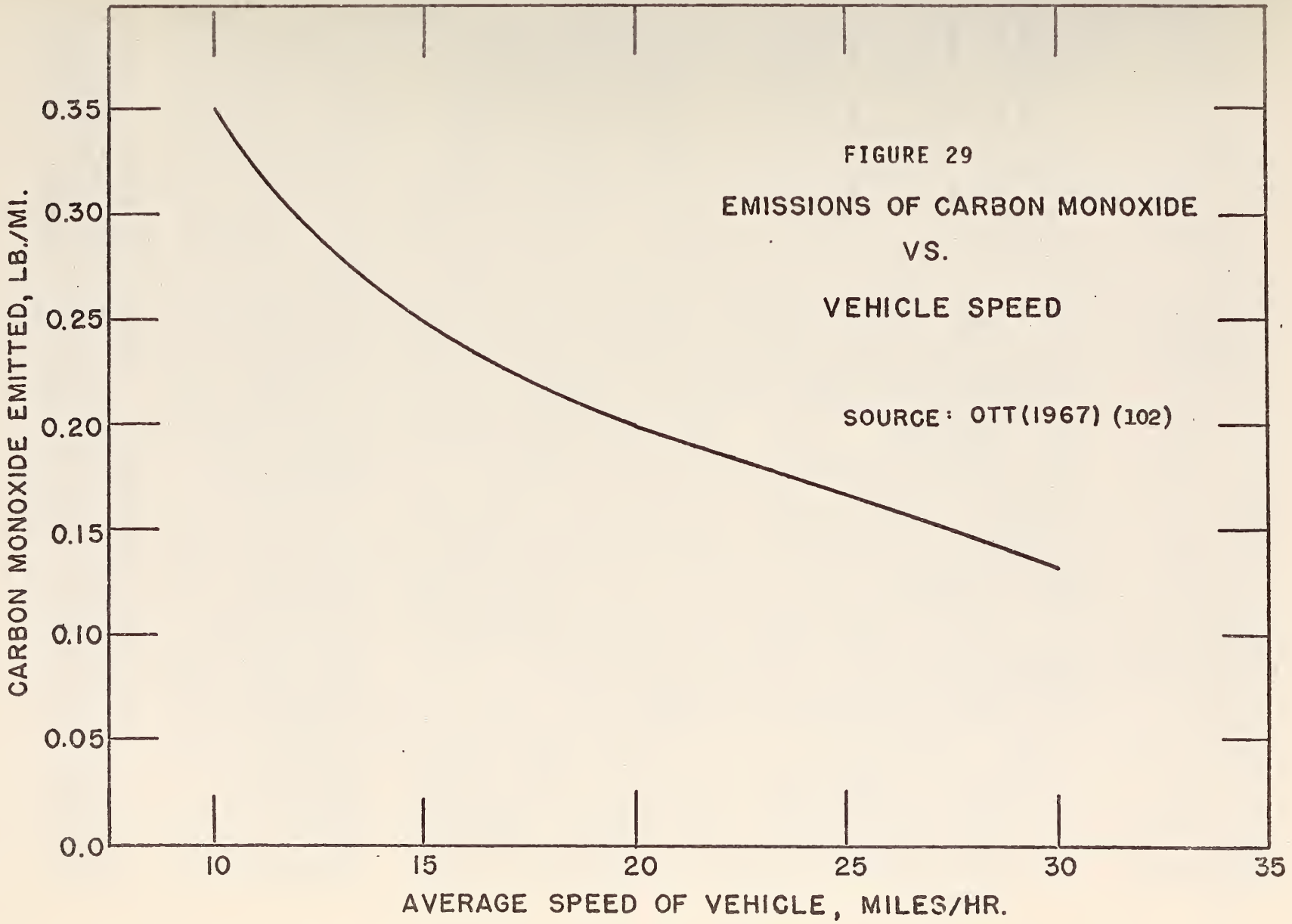


FIGURE 29

EMISSIONS OF CARBON MONOXIDE

VS.

VEHICLE SPEED

SOURCE: OTT(1967) (102)

Sumner Tunnel employs transverse ventilation, hence one would expect the longitudinal air velocity to be due primarily to the piston effect. In longitudinally ventilated tunnels the forced ventilation and piston effect are additive. In either case, increased traffic speeds will not only yield lower initial emissions, but will provide greater total tunnel ventilation.

Reserve capacity and fan speed control are invariably built into tunnel ventilation systems in order to handle peak traffic loadings, without incurring the additional operating expense of constantly running at maximum ventilation capacity. Theoretically, this design approach could be carried one step further by adding fans to augment peak ventilation capacity. However, ventilation ducts in existing tunnels are of a fixed size, and the pressure head of the ventilation blowers is similarly fixed by the peak flow requirements for that duct size. Because the blower head requirement is a function of (gas mass flow rate)^2 through the fixed-size duct, an attempt to double the peak ventilation flow rate will cause a four-fold increase in the head loss. Depending on the head-capacity characteristics of the original fan, it is probable this higher head will not permit the original fan to develop any more than a fraction of its low-head flow capacity. Thus reduction of pollutant concentration by flow augmentation for an existing tunnel will depend on the degree, if any, of over-design in the original ventilation system, and the head-capacity characteristics of the original blower. This combination of factors will obviously be different for each tunnel, and would require checking of the initial ventilation system design. Alternately, it may be possible to replace the blades on the original fan to yield head compatibility with the additional high-head unit. The addition of intermediate ventilation shafts is another possibility but this will be feasible only for specific tunnels, and this consideration is beyond the scope of this report.

The head increase problem incurred in any flow augmentation scheme will also arise if bulk tunnel pollution control techniques are employed in an existing tunnel. In the latter case, the head increment would be incurred at constant flow. The total head loss would be a function of the flow resistance of the pollutant control process placed in series with the ventilation system. Here again, the original blower head-capacity curve is the ultimate determinant of process selection and feasibility.

Direct vehicular exhaust control techniques have received the major share of attention and implementation. There appears to be no question that every possible effort has been, and will be made, to protect the present industrial

and private investment in the internal combustion vehicular engine by the further development of source controls. Present differences between Federal authorities and the automotive industry concern timetables for emission reduction, rather than the degree.

In a recent paper[103] reviewing the progress of the automotive industry in controlling emissions, it was claimed that 1971 model passenger cars had 85% less hydrocarbon emissions and 65% less CO emission than earlier uncontrolled models. Jensen also indicated that similar reduction in NO_x emissions could be expected for 1973 model cars. No data were introduced to support the magnitude of the claimed emission reductions, but nevertheless, engine design changes in recent model years have already produced significant reductions in exhaust emission. While previous introduction of low-emission vehicles is now affecting "average" vehicle emissions, and will continue to lower this average as the vehicle population includes a greater proportion of these low-emission vehicles, prediction of the quantitative effect of the programmed reductions is desirable, and this will be done below.

Because source control techniques appear to be succeeding, projected emission standards and air quality criteria goals that formerly appeared unattainable are now possible, if not probable. Tunnel ventilation system design must take into account the new Federal air quality criteria, which are likely to be considerably more stringent than present allowable pollutant concentration limits. The most recent information on primary standards[104] is given in Table 24, and the proposed CO level (maximum 1-hour concentration once a year) of 17.2 ppm is particularly important when compared to present design limits of 100 to 200 ppm CO. In view of the proposed Federal standards for automotive emission reduction in the 1971-1980 period, it appears certain that the average CO emission level will continue to decline, and with respect to this pollutant, allowance must be made in ventilation design for this decrease. However, it is also virtually certain that, as exhaust control technology proves to be effective in reduction of peak pollutant loadings, the allowable in-tunnel ambient pollution concentration limits will also be lowered.

Exhaust Emission Projections

The design basis for the ventilation of vehicular tunnels is the peak traffic load (exhaust emission rate) plus a maximum CO concentration limit. It should be noted that prevailing vehicular CO emission data obtained from test data at the time of the ventilation design are now used as the

TABLE 24

NATIONAL AIR QUALITY STANDARDS PROPOSED BY EPA

PRIMARY STANDARDS

Air Pollutants	$\mu g/m^3$	ppm
CO		
Max. 8-hr. conc. once a year	10,000	11.4
Max. 1-hr. conc. once a year	15,000	17.2
HC		
Max. 3-hr. conc. from 6 am. to 9 am. once a year	125	--
NO_X		
Annual arithmetic mean	100	0.19 (as NO_2)
24-hr. conc. once a year	250	0.47 (as NO_2)
SO_X		
Annual arithmetic mean	80	0.21 (as SO_2)
24-hr. conc. once a year	365	0.96 (as SO_2)
Particulate matter annual geo. mean	75	--
Max. 24-hr. conc. once a year	260	--
Photochemical oxidants		
Max. 1-hr. conc. once a year	125	--

Adapted from Pollution Engineering, 1971

basis for estimating ventilation needs. Thus, for the Straight Creek Tunnel ventilation system design[105], CO emission test data obtained in 1964 road tests were utilized. Ventilation needs for the year 1990 were also calculated based on these 1964 emission data. Because 1964 is a year representative of virtually uncontrolled exhaust emissions, it may serve a conservative design base, but a 26-year extrapolation in the light of the success of source control techniques represents an unknown degree of over-design.

In order to properly define the tunnel air pollution problem in a time-variant framework, it is necessary to review and quantify the effects of mandated automotive source controls on future emissions. Exhaust source control techniques have been operative for several years, and will be increasingly implemented at higher efficiencies in the immediate five-year period. The question is: how much will this control strategy affect tunnel environments in the next 10 years, and will further in-tunnel control be necessary? As noted above, tunnel ventilation systems appear to be designed for the emissions existing at the time of design initiation, but are then written off over a 20 to 30 year period of decreasing emissions. Systems amortized over this period should be so designed as to take advantage of a decreasing ventilation load. With the recent development of valid predictive models, together with the firming of emission control timetables, it is now possible to predict the course of future automotive emissions.

Table 25 lists the exhaust emission standards proposed by both the Federal government and the State of California. These standards must be considered tentative, inasmuch as Federal standards are presently being formulated, and are expected to be announced some time in 1971. If California standards prevail, then 1975 model cars will show a decrease of 77.3% in hydrocarbons, 47.8% in CO, and 75% in NO_x in exhaust emissions compared to 1971 models. Although Table 25 emphasizes the California standards, recent news announcements[106] indicate that the Environmental Protection Agency may accelerate the California timetable in its own Federal schedule. Should this be the case, then the schedule indicated in Table 25 will prove to be conservative, assuming of course, full compliance by the automotive industry. The data of Table 25 may be combined with passenger car (and truck) population composition data to generate a quantitative prediction of future emissions, and this type of analysis has been developed in detail by Blum[107] in his Model I presentation.

Previous estimates of future automotive exhuast emissions[108] have made allowance for the projected increase in the total automobile population. This is a necessary approach when computing the net effect of control technology

TABLE 25

EXHAUST EMISSION STANDARDS AND GOALS

	Emission Levels, Grams per Mile			
Year	HC	CO	NO_x	Particulate
1970	2.2	23.0		
1971*	2.2*	23.0*	4.0*	
1972*	1.5*	23.0*	3.0*	
1973	2.2	23.0	3.0	
1974*	1.5*	23.0*	1.3*	
1975*	0.5*	12.0*	1.0*	
1975	0.5	11.0	0.9	0.1
1980	0.25	4.7	0.4	0.03

Evaporation Losses - 6.0 grams per test in 1970 in California and 1971 nationwide.

*California only.

on atmospheric pollution in urban areas, and where total emissions are of prime interest. However, vehicular tunnels have a finite length, and a design base maximum traffic capacity at a fixed emission level. Emissions in tunnels will thus be affected only by the age-composition of the automobile and truck population, and not by the expansion or gross numbers of the car and truck populations.

Age-composition data have been calculated by Blum[107] from figures published in Automobile Facts and Figures[109] and these data on automobile longevity are presented in Table 26. In the absence of information on changes in ownership patterns or automobile longevity with economic conditions, it may be assumed that Table 26 represents a composition that will be relatively stable with time, and that the age distribution of 1963-1964 will continue to hold for the 1970-1980 period. Blum derived a statistical model relating the total rate of vehicular emissions to driving characteristics and vehicle emission controls, and while this model is best projected by computer, Table 26 does allow arithmetic approximation of Blum's Model I analysis, using the emission control schedules of Table 25.

As Blum points out, Table 26 indicates that, while the average age of the automobile population is approximately 6 years, the median life of an individual vehicle is 11 years. Further, while cars 16 years and older constitute 1 to 2% of the total car population in any given year, 10% of the cars produced in a model year are still in use 16 years later. Because of this longevity characteristics, there is a time-lag in the effect of any change in emission on overall emission levels. Thus, even if all cars produced in 1972 were to have little or no emissions, it would be 1978 (6-year average age) before the 1972 and later model cars would make up 50% of the total car population, 1981 before they would make up 75% of the population, and 1986 before they would have replaced 95% of the older cars. Truck replacement is even slower[110] with a 50% replacement age of 7 years, 75% replacement time of 13 years, and a 95% replacement of 18 years. These data make no allowance for any increase in the rate of production of new models, and are thus conservative in terms of the effects of exhaust controls. Any increases in the rate of new model production (with controls) will be reflected in a decrease in average age and a greater influence on total emissions of the new vehicles.

Combining the above data with the projected control timetables enables a stepwise arithmetic calculation of comparative CO and HC emissions for the years 1970, 1975 and 1980. These calculations are presented in the Appendix II

TABLE 26

AUTOMOBILE LONGEVITY

"A" Age of Car (Years)	Fraction of Cars (A-1) Years Old in Preceding Year Surviving to Become "A" Years Old in:		Fraction of Cars Originally Produced that had Survived "A" Years in:	
	1963	1964	1963	1964
2 - 3	.999	1.000+		
3 - 4	.999	.991	.999	.991
4 - 5	.990	.990	.990	.981
5 - 6	.974	.975	.964	.956
6 - 7	.957	.952	.922	.910
7 - 8	.936	.916	.863	.834
8 - 9	.906	.909	.781	.758
9 - 10	.856	.859	.669	.651
10 - 11	.813	.822	.544	.535
11 - 12	.780	.770	.424	.412
12 - 13	.764	.753	.324	.310
13 - 14	.769	.752	.249	.234
14 - 15	.752	.757	.187	.177
15 - 16	.773	.731	.145	.129
16+	.797	.825	.116	.107

Median Automobile Life = 11 Years (Approx.)

Average Age of Automobile Population = 6 Years (Approx.)

and the results are plotted in Figure 30. It is obvious that, despite the time-lag effect, the degree of control programmed is so sharp that the indicated reductions in average emissions are considerable. The average hydrocarbon emission will be reduced from 660 ppm in 1970 to 156 ppm in 1980, and the average CO emission will decrease from 25,790 ppm to 6,120 ppm over this same period. This calculation makes no assumptions concerning the nature of the exhaust control technology to be employed, but should it be of a non-integral nature, such as a catalytic converter, which can be added to older models, then the decrease in emissions would be even more marked than shown in Figure 30.

The indicated four-fold reduction in CO and hydrocarbons in the immediate decade resulting from the imposition of exhaust controls is substantially equivalent to a four-fold increase in tunnel ventilation capacity over original design levels (discounting the decreases in average emission levels that have already occurred in the 1964-1971 period). The question naturally arises as to whether or not auxiliary tunnel ventilation or pollutant removal measures are, or will be, required in view of the apparent effectiveness of the exhaust control approach. The only answers that can be ventured at this time are:

1. If no changes are made in the allowable ambient tunnel concentration levels used as the initial ventilation system design basis, then additional controls will not be required, and source control will eliminate any excessive tunnel pollutant loading problems.
2. Tunnel control technology will be needed only in the event that ambient quality criteria call for pollutant reductions in excess of those presently scheduled *via* source exhaust controls.

Because national primary ambient air quality criteria are still in preparation, it will be necessary to review the control problems at the time these standards have been formulated and accepted.

Tunnel Air Treatment: Problem Statement

The design base used in assessing the feasibility of various tunnel air treatment techniques was a 1-mile long, single-tube tunnel with a ventilation air rate of 250,000 CFM. Data on the gaseous pollutant volumetric emission rates for this base tunnel are listed in Table 27. These values are

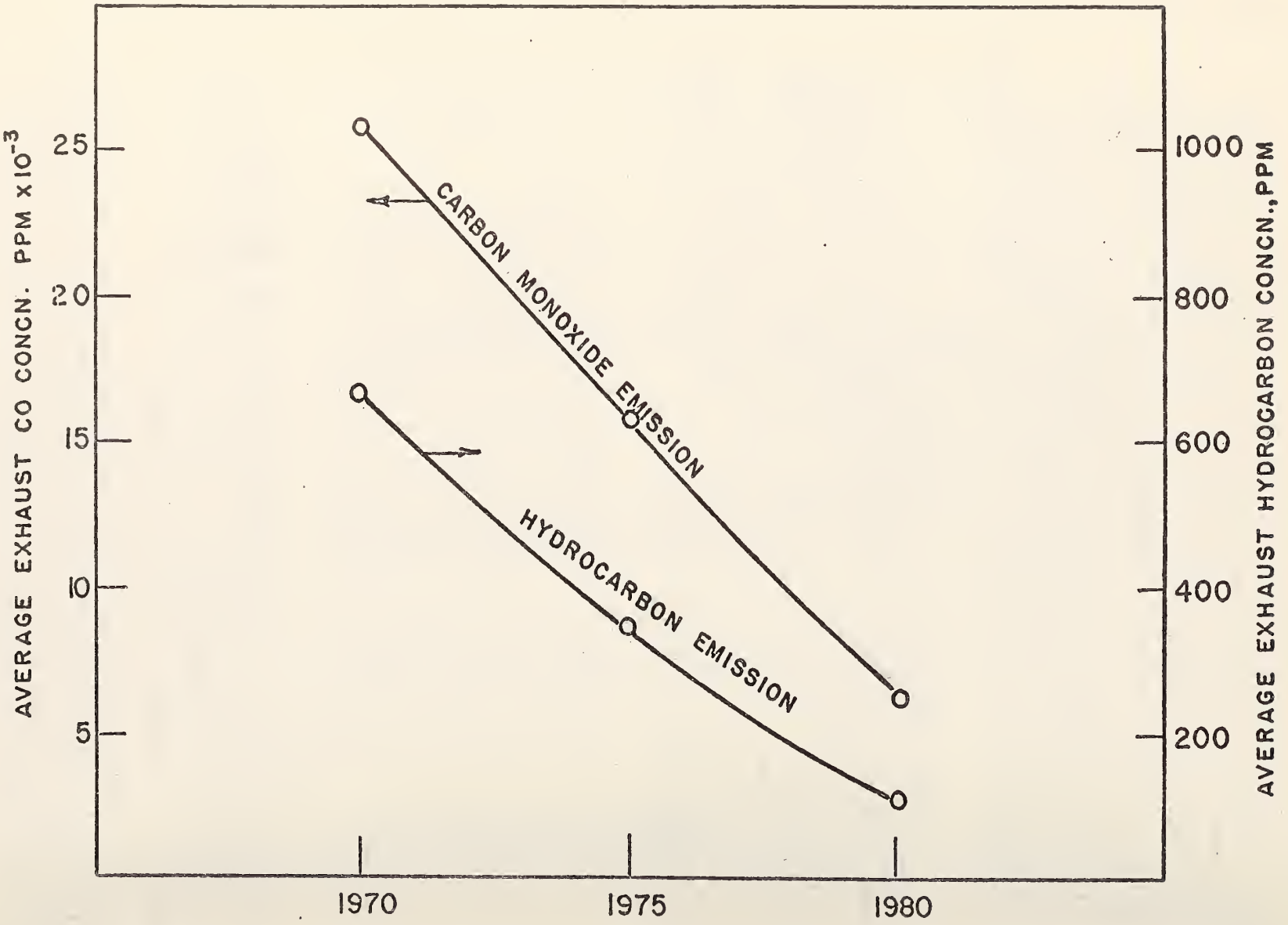


FIGURE 30 - PROJECTED AVERAGE EXHAUST EMISSIONS, PERIOD 1970-1980

TABLE 27

TUNNEL POLLUTANT LOADINGS

Basis: 1 Mile Tunnel Length
Level Single Tube, 2,000 Vehicle/Hr.
40 Mile/Hr. Average Speed

Component	$Ft.^3/Hr.$ [a]	ppm	Lbs./Hr. [b]
Carbon Monoxide	2,260	150	163.5
Ethylene	28	1.86	2.02
Acetylene	28	1.86	1.88
Hydro carbon	68	4.53	17.6 [c]
Nitrogen Dioxide	8	0.53	0.95
Nitric Oxide	28	1.86	2.17
Acrolein	10	0.67	1.44
Formaldehyde	22	1.47	1.70
Sulfur Dioxide	16	1.07	0.26
Carbon Dioxide	10,170	678	1,156

(a) Letter from F. Roehlich, MSA Research, March 19, 1971 to B. Lerner, Patent Development Associates

(b) Based on 70°F. tunnel temperature

(c) Assumed mol. wt. = 100

Assumed Ventilation Air Rate = 250,000 cfm.

also stated in terms of parts per million (volumetric) and mass rates to provide comparisons with normal industrial pollution equipment capabilities. With the exception of CO, the ppm pollutant concentrations listed in Table 27 are representative of treated gaseous effluent concentration levels for most gas processing operations, rather than concentration inputs to such processes.

A preliminary measure of the very small magnitude of the pollution loading rates may be obtained by comparing the loadings to the assumed ventilation air rate, which is relatively low. The ventilation air rate of 250,000 CFM is equivalent to a weight rate of 1,125,000 lbs/hr. Thus, if total air treatment is to be considered, then it will be necessary to process more than 500 tons/hr of air in order to remove less than 25 lbs/hr of pollutants other than CO and CO_2. In the case of the individual pollutants, the selectivity requirement is much more extreme. For example, to remove the eye irritants, acrolein and formaldehyde, involves the removal of 3.2 lbs/hr from the total 1,125,000 lbs/hr air, and for NO_x, 3.0 lbs/hr.

The combination of high total gas processing capacity with the extremely low concentration levels indicated in the Table 27 data, calls for a removal selectivity which is highly unique for industrial air treatment techniques, and even for most specifically sensitive pollution control operations such as adsorption. The closest processing analog with similar selectivity requirements is extractive metallurgical operations involving the removal of a rare metal such as uranium from a low-concentration ore, typically 0.5% for uranium oxide. In the latter case, not only is the concentration 500 to 1000-fold higher than for indicated pollutant concentration levels in tunnel ventilation air, but the cost-benefit relationships for uranium are quite different than for pollutants, where the health benefits are still not fully defined.

The tunnel air treatment problem becomes even more complex when each pollutant is matched against the removal process judged to be most applicable under normal circumstances. This has been done in Table 28, which briefly summarizes the results of an evaluation of the current optimum control process art with respect to each pollutant. Also given in Table 28 are particulate data. The process selections listed are preliminary and "apparent" from an engineering point of view; they should not be considered feasible or recommended at this point. It is obvious from Table 28 that a combination of processes will be required for the removal of most or all of the pollutants. Essentially, the 1,125,000 lbs/hr of tunnel air must be processed several

TABLE 28

PRELIMINARY SINGLE-POLLUTANT OPTIMUM PROCESS INDICATION

Component	ppm	Process Indication
Carbon Monoxide	150	Catalytic Oxidation
Ethylene	1.86	Catalytic Oxidation
Acetylene	1.86	Catalytic Oxidation
Hydrocarbons	4.53	Carbon Adsorption
Nitrogen Dioxide	0.53	Water Absorption
Nitric Oxide	1.86	Zeolite Adsorption
Acrolein	0.67	Water Absorption
Formaldehyde	1.47	Water Absorption
Sulfur Oxide	1.07	Water Absorption
Carbon Dioxide	678	Water Absorption
Particulates[a] (including benzene-soluble organics) (150)	$\frac{\mu g/m^3}{500}$	Electrostatic Precipitation

(a) Letter of December 30, 1970 from F. Roehlich, Jr., MSA Research to B. J. Lerner, Patent Development Associates, Inc.

times to yield multi-pollutant removal capability. One of the hidden difficulties in Table 28 is the fact that each process was selected for the individual pollutant, neglecting the interference and interaction effects known to exist. For example, gas absorption of NO_2 in water is a standard operation for this component, but it is doubtful if this soluble acid-gas can be absorbed in the presence of much higher concentrations of another acid-gas: CO_2. Further, even when considered alone, the concentrations of NO_2 in tunnel gas are far below the concentrations normally treated in sorption operations, and indeed, below usual effluent treated gas concentrations.

The selections listed in Table 28 are based entirely on consideration of the nature of the single pollutants without reference to their tunnel site of generation. Adding this latter factor leads directly to feasibility determinations, which will be considered in detail below. However, it may be noted here that the closed-system aspect of application of tunnel air treatment in situ immediately rules out some of the standard treatment processes of Table 28, such as aqueous absorption. Re-use of wet-scrubbed air within a tunnel will not be permissible because of the 100% humidity characteristic of such treated air. This points up one of the particularly unique aspects of the tunnel ventilation problem; the concentration of pollutants is so low that impurity-contribution or substitution by a treatment operation constitutes a secondary pollution problem.

Tunnel Ventilation Costs

As indicated above, an alternate to tunnel air treatment for pollutant removal is increased tunnel ventilation by means of fan addition. Although this latter method may involve possible reconstruction problems for existing tunnels, such reconstruction is much more probable in the case of pollution control equipment installation. This factor aside, the assessment of incremental tunnel ventilation costs provides a yardstick against which the comparative capital and operating costs of any individual pollution control method can be measured. While such cost comparisons are by no means direct, they can serve as a preliminary guide, until sufficient data become available to permit valid cost-benefit calculations. Tunnel ventilation base costs provide a conservative measure inasmuch as a 100% increase in ventilation flow theoretically provided for a 50% decrease in concentration for all air pollutants in the tunnel air. On the other hand, the pollution control techniques considered below are generally selective for one or two specific contaminants. This limited selectivity property is partly offset by the higher efficiency of the pollution control process, so that direct cost comparisons

at this stage of changing ambient standards becomes uncertain.

Table 29 presents a tabulation of capital costs of fan and motor combinations to yield a peak ventilation air rate of 250,000 CFM against different head losses. It should be noted that this is an arbitrary example and does not necessarily apply to all types of tunnels and tunnel ventilation systems. These calculations were based on the data contained in Project No. 170-3(212) (1966) Report on Ventilation Studies of the Colorado Department of Highways for the 1.6 mile Straight Creek Tunnel. These latter data were corrected to sea level horsepower requirements and corrected for the cost index changes between 1964 and 1970. The basis for Table 29 was the use of three fans: 1 supply, 1 exhaust and 1 standby, each of 250,000 CFM rating, a choice deliberately made to provide a maximum (and thus conservative) cost basis. Additionally, extrapolated unit prices of the motor-fan combinations in Table 29 were known to be intrinsically high; direct quotation from a manufacturer on two 125,000 CFM vane-axial motor-fan combinations at 1.5" static head indicated a cost of $11,250 for the pair. This compares with the Table 29 value of $18,500 for the same flow capacity at 1" static head.

Table 29 provides a base cost of the blower augmentation route of providing either incremental volume or static head (or both). Thus, to provide an incremental 250,000 CFM flow for an initial 250,000 CFM tunnel peak ventilation rate at a 2" static pressure head, would require a total capital charge for the additional blowers of $102,600. The new head of 4.2" W.G. would satisfy the squaring of the original head requirement, and the annual capital charges for the added system on a 30-year amortization schedule would be $6,680. Additionally, Table 29 may be used to estimate the capital costs incurred in increasing the static head at constant delivered volume, a situation that would result from the use of a fixed-bed pollution control unit in a ventilation tunnel. Table 29 shows that an incremental 3" W.G. head would involve a capital cost increment of $26,100, and an annualized charge increment of $1,700.

The tunnel ventilation fan operating costs were also adapted from the Straight Creek Tunnel Design report, and the electrical energy costs were assumed to be the same as in the report. In the absence of a specific reference tunnel location, the electrical power cost data for any location may be used as a reference case, provided the detailed cost breakdown is provided, as was the case in the Straight Creek Tunnel report. The calculated data are summarized in Table 30, and attention is called to the assumed operating rate of half-peak load for 365 days/year plus peak load of 44 hours per week.

TABLE 29

ESTIMATED 1970 TUNNEL VENTILATION BLOWER CAPITAL COSTS
AS FUNCTION OF HEAD REQUIREMENT

250,000 CFM RATE

Total fan operating pressure	Number of fans & motors installed (a)	Unit Price fan and motor (b)	Total cost fans and motors	Installation cost - 3 Fans	Combined Total	Annual Capital Charges (c)
1"	3	$18,500	$55,500	$21,000	$76,500	$4,980
3.1"	3	$25,000	$75,000	$21,000	$96,000	$6,250
4.2"	3	$27,200	$81,600	$21,000	$102,600	$6,680

(a) 1 Supply Fan, 1 Exhaust Fan and 1 Standby Fan on wheels, each fan rated at 250,000 CFM.

(b) Assumed 30 year life and 5% interest rate. Capital recovery factor 0.0651.

(c) Cost estimated using scaling factor of 0.96 and Marshall & Stevens Process Industry Equipment Cost Index. 1964 base price from Straight Creek Tunnel Report.

TABLE 30

OPERATING COSTS OF TUNNEL VENTILATION BLOWER
AS FUNCTION OF HEAD REQUIREMENT

250,000 CFM RATE [a]

ΔP in. of water	Total Power (BHP)	HPH = HP x 5524	Consumption KWH = HP x 0.746	Demand KW = HP x 0.746	Consumption Cost $ [b]	Demand Cost $ [c]	Total Power Cost $
1"	104	575,000	430,000	78	3,955	140	4,095
3.1"	324	1,790,000	1,335,000	249	11,655	448	12,103
4.2"	440	2,430,000	1,812,000	328	15,695	590	16,285
6.0"	628	3,470,000	2,565,000	468	22,095	842	22,937

(a) Assumed 1/2 peak load operation for 4,380 hours/year, plus peak load for 1,144 hours/year.

(b) Assumed consumption cost: First 20,000 = $275.00; next 100,000 @ $0.0096; next 170,000 @ $0.0090; excess @ $0.0085. No fuel adjustments considered.

(c) Assumed demand cost: $1.80 per KW.

The total annual power cost for a nominal 250,000 CFM ventilation air system ranges from $4,095 at 1" static head to $22,937 at a 6" static head. Again, the data of Table 30 provide a measure of not only the operating costs of augmented ventilation, but also the operating costs of incremental power necessary to force the air through any added piece of pollution control equipment. The combined capital and operating charges for a 250,000 CFM ventilation rate, as taken from Tables 29 and 30, ranges from a total of $9,075 at 1" static pressure, to $22,965 at 4.2" static pressure.

It should be obvious at this point that if insertion of a pollution control unit in the tunnel ventilation system incurs a head loss of 1" or more, then additional fan capacity will be required. However, the use of this fan alone, without installation of the pollution control unit, is itself capable of reducing the pollutant concentration levels. Thus, the cost-benefit potential of pollution control unit with significant head loss must outweigh not only the capital and operating costs of the additional fanpower required, but also the pollution improvement benefit of the ventilation potential presented by the fan increment itself. While this will depend on the head-capacity curves of the original fans in existing tunnels, pragmatically this would indicate that the head loss across the pollution control equipment be held to less than the normal head rating of the original fan, and preferably to a negligible head loss. There are very few pollution control processes that have an inherently low or negligible pressure loss characteristic, but in view of the incremental ventilation alternate to high head-loss equipment, the low-loss equipment will possess a two-fold economic advantage.

Process Feasibility: CO and Hydrocarbons

Because the presence of CO and hydrocarbons, including oxygenated hydrocarbons, is the result of incomplete combustion, completion of combustion is an obvious method of removing these pollutants from tunnel air. However, although CO and hydrocarbons constitute the major fractions of the pollutant load, and oxidative removal of these fractions is the preferred industrial treatment method, inspection of Table 27 led to the preliminary judgement that thermal oxidation was not feasible. This conclusion is based on the fact that the concentration levels of combustibles in the tunnel air are several orders of magnitude lower than any known feed stream to a thermal incineration process, and that the ambient temperature of the tunnel air presents no thermal advantage for such a process. All of the energy input and removal for the required thermal cycle must be externally supplied, and thermal incineration was not considered feasible

or treated in depth. However, some preliminary calculations were carried out to assess the magnitude of the economics of a hypothetical heat/cooling cycle.

There are two types of thermal oxidation practiced; direct flame and indirect heating. Because the products of combustion of direct flame incineration would probably add to the tunnel air pollutant concentrations of the same or greater concentration levels as those originally present in the tunnel air, this method was judged not applicable. Assuming, therefore, indirect heating, and a temperature increment of 1000°F, preliminary heating and cooling cost estimates have been made. For the heating portion of the cycle, using a thermal efficiency level of 50%, natural gas requirements of 5.56×10^5 CFH are indicated. If a conservative estimate of cooling cycle operating costs is made, taking these as equal to the natural gas costs for heating, then the minimal annual operating costs for the thermal cycle operation would be $99,200, based on a total annual operating time of 2,288 hours. Even without system capital charges, this figure is far in excess of the auxiliary ventilation costs. Further, it should be noted that the use of 5.56×10^5 CFH of natural gas as fuel produces a total of 3.76×10^6 CFH of combustion gases with their own secondary pollution loading. These would have to be vented from the tunnel by a separate flue, but since they amount to about 25% of the total ventilation air rate, provision for this in existing tunnels would involve considerable construction. Thus, both technical and economic indications for thermal oxidation appear to be negative.

The normal industrial catalytic oxidation process employs operating temperatures several hundred degrees lower than those used in thermal oxidation techniques, but these nevertheless would constitute appreciable thermal cycling costs for tunnel air treatment. What is required is an ambient, or near-ambient temperature catalytic oxidation operation, to avoid both thermal cycling and the secondary pollutant problem of auxiliary fuel-burning to supply thermal energy. While a literature search failed to find any industrial low-temperature oxidation processes for pollutant removal, two recent laboratory developments appeared to satisfy the low-temperature requirements. The first of these is a "commercial" 60% MnO_2/40% CuO catalyst tested by Cannon[58] on automotive exhaust and reported to have a threshold activity temperature of 25°C. Despite several direct inquiries, no further information could be elicited on this material, which appears to be similar to Hopcalite. Because the test conditions reported for this catalyst were very encouraging, calculations of the required catalyst volume and heat loss were made to determine the feasibility of large scale appli-

cation to the 250,000 CFM base tunnel air case:

Cannon Catalyst: 60 MnO_2/40 CuO

Test Conditions: Space Velocity = 10,880 hr^{-1}
Operating Temperature = 25°C
Catalyst Density = 0.88 g/ml

Volumetric Air Flow = 250,000 CFM

a. Catalyst Volume Required

$$\text{Volume} = \frac{(250{,}000)(60)}{10{,}880} = 1{,}380 \text{ CF}$$

b. Pressure Drop

Without information on the physical form of the catalyst, it is necessary to assume that it would be equivalent to 4-10 mesh granules in fixed-bed form. Assuming further a linear velocity of 80 ft/min, typical of granular fixed-bed gas processing:

Case I: Face Velocity = 80 FPM

$$\text{Bed Area} = \frac{(250{,}000 \text{ CFM})}{(80 \text{ FPM})} = 3{,}125 \text{ ft}^2$$

$$\text{Bed Thickness} = \frac{(\text{Volume})}{(\text{Area})} = \frac{(1380)}{(3125)} = 0.441 \text{ ft}$$

$$= 5.3 \text{ inches}$$

Weight of Catalyst

$$= (1380 \text{ CF})\ (0.88)\ (62.4 \text{ PCF})$$
$$= 7{,}580 \text{ lbs}$$

From Figure 1, Appendix II:

Pressure Drop/inch depth at 80 FPM = 0.725 in.W.G.
Pressure Drop through 5.3-inch bed
$= (0.725)\ (5.3) = 3.84$ in. W.G.

The above pressure drop calculation was based on a normal linear gas flow velocity through a fixed granular bed, and the ΔP of 3.84 in. W.G. may be excessive for ventilation blowers with limited heads. It is therefore desirable to calculate bed area and thickness for the case of limited blower head, and this latter value can now be assumed as not to exceed 1 inch W.G.

Case II: Face Velocity = 45 FPM (Trial & error from Figure 1, Appendix II)

$$\text{Bed Area} = \frac{(250,000)}{(45)} = 5,560 \text{ ft}^2$$

$$\text{Bed Thickness} = \frac{(1,380)}{(5,560)} = 0.2485 \text{ ft}$$

$$= (0.2485)\ (12) = 2.98 \text{ inches}$$

From Figure 1, Appendix II, at 45 FPM

Pressure drop/in. depth = 0.33 in. W.G.

Total Pressure Drop = (2.98) (0.33) = 0.985 in.

The reduction in pressure drop from 3.8" to 1" W.G. is accomplished by the reduction in face velocity from 80 to 45 FPM, and a simultaneous decrease in bed thickness from 5.3 to 3 inches. However, in order to conserve the initial space velocity value of 10,800 hr^{-1}, the bed flow area increases from 3,125 ft^2 to 5,560 ft^2. This is a 78% increase in bed area, which will be reflected in the capital cost of the unit in terms of the extra bed construction required. However, the economic calculations outlined below deliberately neglect this factor, to provide the most optimistic cost estimate for oxidation. The optimum fixed-bed unit in terms of the head-loss/bed area capital cost relationship can be determined from the capital and operating costs difference for the blowers involved, from the data of Tables 29 and 30, should this comparison be required.

While the ambient-temperature, MnO_2/CuO catalyst appears to offer reasonable prospects of applicability to the tunnel air problem, pending further development effort, there are two additional aspects to be considered. First, the Cannon tests were made directly on automotive exhaust, and the concentrations of pollutants were approximately 150 times as great as those to be encountered in tunnel air. Second, there is evidence that complete oxidation of the hydrocarbon fraction by ambient-temperature catalytic oxidation may not be possible, and certain partially-oxidized hydrocarbons, such as acrolein and formaldehyde, are eye irritants which are much more discomforting than their inert precursors. The technical feasibility of catalytic oxidation employing manganese-copper oxide catalysts may be considered to be tentatively promising, and further direct testing at tunnel air pollutant concentrations is strongly recommended.

One of the well-established feasibility factors for catalytic oxidation of automobile-derived pollutants is the susceptibility of the catalyst to poisoning by the lead salts and other particulates present in auto exhaust. Based on exhaust catalytic converter experience continuous long term

use of a fixed-bed catalytic oxidation process is not feasible without provision for pre-removal of particulates, and a cost evaluation must consider the combined system. This consideration also applies to the second type of low-temperature oxidation catalyst developed by Sutt[111] which consists of a transition metal oxide supported on activated carbon. When used on ammonia synthesis gas, the lowest temperature at which plus-90% oxidation was obtained was 120°C, although there were indications that this was not the lowest thermal activity level achievable. While this catalyst appears promising, the data provided are laboratory scale, with space velocities of only 200 hr^{-1} at ambient pressure. Tests at higher pressures (400 psi) and higher space velocities of 4800 hr^{-1} showed only 50% conversion, so that extrapolation to tunnel design is uncertain. However, because of the activated carbon base for this oxidation catalyst, it is probable that the feasibility and economics of its application will closely parallel that of activated carbon adsorption, treated below.

Price information on the MnO_2/CuO catalyst tested by Cannon was not available directly, and it was therefore assumed that this was a precipitated material. From published price data on the component oxides so prepared, it was estimated that the cost of the mixed oxides was approximately $1.80/lb. Provided that bulk quantities of this catalyst could be obtained at this price, the catalyst cost for the required 7,580 lbs would be $13,644. This latter figure involves considerable uncertainty because of the quantity involved and the present lack of available information on commercial sources.

Because of the similarity between fixed-bed catalytic oxidation operations and activated carbon adsorbers, it was felt that available capital costs data for the latter units could be applied to the catalytic operation, with due correction for the cost of catalyst and accessories. Because adsorbers (and catalytic oxidation units) larger than 50,000 CFM have not yet been built, it is necessary to extrapolate from the 10,000 to 50,000 CFM range to the 250,000 CFM level of tunnel air flow of the present problem. From HEW, AP-68[112] the extrapolated installed cost of an activated carbon adsorber treating 250,000 CFM of air, including superheater, condenser decanter, blower and motor, cooling tower, filters, carbon, filter housing and vessel, was estimated to be $295,000. For catalytic oxidation, it was assumed that the accessory charges were equivalent to 50% of the total installed cost, giving an estimated capital cost of $147,000. However, this figure contains a carbon charge of $0.45/lb, and correcting for the difference between this price and the $1.80/lb catalyst cost gives an incremental cost of $10,233, for a total of $157,233.

Depending on catalyst life with and without pre-removal of particulates, a situation that should be experimentally determined for the low tunnel air particulate loading of 500 $\mu g/m^3$, it probably would be cheaper to periodically replace the catalyst rather than install a suitable particulate-removal device such as an electrostatic precipitator. Lack of catalyst cost and life data does not allow a firm estimate at this time, but assuming a 3-year replacement schedule at the above-estimated catalyst cost, plus 35% for the labor involved in change-over, the annualized catalyst charge would then be $4,775.40, and the particulate control unit is eliminated.

The write-off period for pollution control equipment will vary with the potential corrosion severity of the process and system handled, but in any event will be faster than for a purely mechanical unit such as a blower and motor. For the comparatively mild conditions expected in ambient-temperature catalytic oxidation, a 20-year straight-line amortization period may be assumed. The capital and operating charges for catalytic oxidation may be summarized as follows:

TABLE 31 - SUMMARY OF CATALYTIC OXIDATION COSTS

60% MnO_2/40% CuO Ambient-Temperature Catalyst

Annual Unit Capital Charge[a]	Annualized Catalyst Replacement Cost	Annual Fan Capital Cost (Table 29)	Total Annual Capital Charges	Total Operating Cost (Table 30)
$9,434	$4,775	$4,980	$19,189	$4,095

(a) Including 20% for taxes, insurance and maintenance.

The total annual capital costs for the catalytic oxidation unit, which will remove only CO and possibly some of the hydrocarbon content, is roughly three times that of the high-head (4.2") Table 29 ventilation blower unit. Again, the anomaly of the additional blower requirement is evident in the economic estimate, and this equipment alone, without the catalytic oxidation unit, is theoretically capable of a 50% reduction of the entire pollution level on a nonselective basis.

Process Feasibility: Hydrocarbons

For the removal of small amounts of hydrocarbons from an air stream, activated carbon adsorption is the method of choice, primarily because of its selectivity and low-concentration capability. A number of discussions were held with

engineering representatives of a major activated carbon supplier with reference to the practicality of a 250,000 CFM scale of operation, which was known to be roughly 10 times that of a large industrial installation. The consensus as to economic feasibility was negative, although technically, there was no indication of scale problems for adsorbable hydrocarbons, although capacity was questionable. On a preliminary basis, removal of a single component or pollutant group from the air stream with a high-head loss fixed-bed operation is an expensive and less-than-ideal method of partial control.

As shown in Table 27, the concentration of hydrocarbons in tunnel air at peak loading, exclusive of acetylene and ethylene, is about 7 ppm. Based on adsorption isotherm data supplied by Pittsburgh Activated Carbon Company, there will be no adsorption of ethylene, acetylene or formaldehyde at the 1 or 2 ppm concentration levels at which these components are present in tunnel air. Based on hexane adsorption data, at 77°F and 1 psia, 30 lbs hexane will be adsorbed per 100 lbs carbon, so hydrocarbon adsorption at 7 ppm (6.86×10^{-5} psia) is probably feasible, although at limited capacity. In order to take a conservative approach to the preliminary design, particularly in the absence of data on the hydrocarbon composition in tunnel air, it was decided to utilize n-butane adsorption data. The n-butane isotherms were supplied by Pittsburgh Activated Carbon Company, and an extrapolation of these isotherms to the region of hydrocarbon concentration in tunnel air is presented in Figure 2 in Appendix II. From this basis:

Activated Carbon Adsorber Design

Part I: Adsorption Cycle:

From Figure 2, Appendix II at 7 ppm HC:

Capacity to saturation = 1.57 lb n-butane/100 lb carbon

Working Charge, at 50% of saturation capacity = 0.785 lb n-butane/100 lb carbon

From Lee (1970) and PACCO data: Face Velocity = 80 FPM

Area of Bed Required $= \frac{(250,000)}{(80)} = 3,125\ ft^2$

Bed Depth: In order to avoid the use of a two-bed system, and the extreme capital costs involved, bed depth was selected by trial and error to yield a single-

bed adsorber capable of operating, with steam regeneration, within a 24-hour cycle. Design is such that steam regeneration can be theoretically accomplished in off-peak load time period.

Bed Depth = 6 inches

Volume of Bed = (3,125) (1/2) = 1,562 CF

Weight of Carbon in Bed (at 30 lb/CF bulk density)

= (1,562) (30) = 46,860 lbs

Weight of Adsorbate to Breakthrough

= (46,860) (0.00785) = 368 lbs

Lb/Hr of Hydrocarbon (Table 27)

= 17.6 lb/hr

Duration of Adsorption Cycle

$$= \frac{(368)}{(17.6)} = \underline{20.8 \text{ hours}}$$

From Figure 1, Appendix II:

Pressure Drop/inch depth at 80 FPM = 0.725 in.W.G.

Pressure Drop through 6-inch bed

= (0.725) (6) = 4.35 in.W.G.

The pressure loss through the fixed-bed adsorber is virtually the same as the head capacity of the 4.2" W.G. blower listed in Tables 29 and 30, and the operating costs of this unit may be added to those of the adsorption equipment (capital cost estimate for the activated carbon adsorber includes the blower).

In the absence of actual system test data, steam regeneration cycle requirements for a uniquely low concentration of 7 ppm hydrocarbon of varying composition can at best be roughly approximated. Mattia[56] presents data for adsorption of a 20 ppm solvent from a 20,000 CFM stream, together with steam regeneration time curves for various blowdown rates. Taking a value of 128 minutes regeneration from the Mattia curve at a blowdown rate of 2000 CFM, and estrapolating linearly to the tunnel air adsorption conditions:

$$\text{CFM Blowdown Required} = \frac{(20\text{ ppm})\ (20{,}000\text{ CFM})}{(7\text{ ppm})\ (250{,}000\text{ CFM})}\ (2{,}000\text{ CFM})$$

$$= 8{,}760\text{ CFM}$$

Lb Steam/Regeneration, assuming 110% blowdown for vessel heatup:

$$= \frac{(8{,}760)\ (492)(128)(18)(1.1)}{(359)(710)}$$

$$= 42{,}900\text{ lbs/cycle}$$

Assuming 50% operational time requirements:

$$\text{No. Cycles/Year} = \frac{(365)(12)}{(24)}$$

$$= 182\text{ cycles}$$

where adsorption time = 20.8 hours, regeneration time = 2.1 hours,

and heating-cooling time = 1.1 hours

While the similar fixed-bed processes of catalytic oxidation and adsorption both appear to be technically feasible, the high flow required in the contact beds may give rise to space requirement problems. This is particularly true in the case of the adsorption operation which requires accessory regeneration equipment such as a large steam boiler, condenser and cooling water, etc. Also, while catalytic oxidation produces no secondary pollution problem, steam regeneration/condensation in an adsorption cycle produces a hydrocarbon-contaminated water st eam to dispose of. If hot inert-gas stripping is used, the hydrocarbon can be burned but then thermal incineration costs must be added. The single-bed, conventional steam-regenerated adsorption system outlined above appears to offer the fewest problems in straightforward application to tunnel air control, but the basic adsorption/regeneration data required for a more rigorous determination of technical feasibility in the constraints of tunnel installations are not available.

As was noted in the economic workup on fixed-bed catalytic oxidation, the capacity of the adsorption system required, 250,000 CFM, far exceeds that of any unit yet built. Extrapolation of economic data to this range is extreme, and extremely uncertain. Again using HEW AP-68[112] curves for installed costs, and extrapolating:

Installed Cost, 250,000 CFM Adsorber = $295,000

Capital Charges:

Assuming 15-year life, 20% taxes and insurance

Annualized Capital Charges = $23,600

Operating Charges:

Steam Costs: Cost/cycle, at $1.00/M lb steam cost

= $42.90

Cost/Year, 182 cycles = $7,808

Blower Cost: From Table 30, 1" W.G.

= $4,095

Total Operating Costs = $11,903

Total Annual Capital + Operating Charges = $35,503

Activated carbon adsorption systems are particularly susceptible to binding and deactivation by particulates, and the economics of particulate removal equipment vs. periodic carbon replacement are indeterminate without information on the rate of loss of adsorption capacity at the 500 $\mu g/m^3$ particulate loading. However, the economics already indicated are not encouraging, compared with the costs of straightforward ventilation increases as shown in Table 29 and 30. Additionally, the carbon system has the limited capability of removing only the heavier hydrocarbon fraction from the pollutant spectrum, and no sorption capability for the critical low-weight hydrocarbons such as acetylene, ethylene and formaldehyde. Thus, this process cannot be recommended at this time.

Process Feasibility: Particulates

The capacity and efficiency of electrostatic precipitators (ESP) are entirely adequate for treatment of tunnel air. In contrast to the proposed catalytic oxidation or adsorption methods for tunnel pollution control, large-scale commercial high-voltage electrostatic precipitation units handle gas flows in the 500,000 to 2,000,000 range, so that a 250,000 CFM capacity is not at all unusual. However, when direct inquiries were made of several vendors of ESP equipment relative to the tunnel air problem, there was unanimous doubt expressed as to the applicability of their units to a gas stream containing the low particulate concentration of 500 $\mu g/m^3$. The reason for this attitude is not difficult to

determine. In the standard units of grains/CF, 500 $\mu g/m^3$ is equal to a value of 0.000219 gr/CF. HEW, AP-51[113] in their summary on Control Techniques for Particulate Air Pollutants reported an extremely low exit loading from a commercial ESP unit to be 0.005 gr/CF. Thus, the concentration of particulates reported in ambient tunnel air is only 4% that of an unusually low-concentration treated gas stream. It therefore appears that the technical feasibility of ESP application to particulate removal at the loadings normally encountered in tunnel air is very doubtful. Preliminary testing would be necessary to modify present negative engineering judgment of the feasibility of ESP extrapolation to the highly-dilute region of particulate loadings.

Assuming a 150 to 200-fold dilution of automotive exhaust in tunnel air, the concentration of particulates in the exhaust itself will be of the order of 0.04 gr/CF. This latter concentration is in the range where agglomeration and inertial removal are effective, and exhaust source control of particulates has already proven to be technically feasible, and is most certain to be utilized when standards are formulated. The impetus for external control of particulates therefore would not seem to exist at this time. Despite the present lack of any data on particulate collectibility by ESP, or the physical nature and properties of the particulates, an exploratory economic analysis of this operation was carried out.

The economic workup of ESP was carried out using the procedures outlined in HEW, AP-51[113] and the cost data contained in this publication and in Walker[99].

Design Capacity (S), ACFM = 250,000

Assuming 50% onstream time requirement:

Annual Operating Time (H) = 4,380 Hours

Purchase Cost (High Efficiency Unit) = $180,000

Installation:

	Low	Typical	High
Installation Factor,%	40	70	100
Installation Cost	$ 72,000	$126,000	$180,000
Purchase Cost	$180,000	$180,000	$180,000
Total Capital Cost	$252,000	$306,000	$360,000

Annual Capital Charges (C)

The simplifying assumptions used in estimating the annualized capital costs in HEW, AP-51 were:

(a) Depreciation of purchase and installation costs over 15 years.
(b) Straight-line depreciation of 6-2/3% on installed costs, plus
(c) Capital charges of taxes, interest and insurance of 6-2/3% of initial capital costs, to give a total annual charge of 13-1/3%.

Additionally, the 1968 equipment costs used in AP-51 were uncorrected to 1971 costs because of the preliminary nature of the cost estimates made.

$$(C) = (0.133)(\text{Cost})$$

Low (C_L) = (0.133)($252,000) = $33,516

Medium (C_M) = (0.133)($306,000) = $40,698

High (C_H) = (0.133)($360,000) = $47,880

Power & Maintenance Costs (assuming no extra fan power)

	Low	Typical	High
Power Costs (K), $/kw-hr	0.005	0.011	0.06
Power Requirements(J), 10^{-3}kw/ACFM	0.19	0.26	0.40
Maintenance Costs(M), $/ACFM	0.01	0.04	0.06

$$G = S(JHK + M)$$

where:

G = annual operating & maintenance costs

S = design capacity, ACFM

J = power requirements, kw/ACFM

H = annual operating time, 4,380 hours

K = power cost, $/kw-hr

M = maintenance costs, $/ACFM

Low(G_L), Typical (G_M), and High(G_H) annual operating and maintenance costs calculated as above are as follows:

$$G_L = \$3,540;\ G_M = \$13,130;\ G_H = \$41,230$$

and, Total Mean Annual Cost = $C_M + G_M = \$53,828$

Using the square root of the sum of the squares of the differences, the high (V_H) and low(V_L) cost variances are as follows:

$$V_L = ((\$7,182)^2 + (\$9,590)^2)^{1/2}$$

$$= \$11,940$$

$$V_H = ((\$7,182)^2 + (\$28,100)^2)^{1/2}$$

$$= \$28,950$$

Therefore:

Lower Cost Limit = \$53,828 - \$11,940

= \$41,888

Higher Cost Limit= \$53,828 + \$28,950

= \$82,778

The high cost variance amounts to more than 50% of the mean cost of \$53,828, so that the chances of exceeding the mean cost is much better than a cost under-run. The annual ESP costs are a good deal higher than those of the treatment techniques previously estimated, and it may be concluded that, in addition to being technically doubtful, ESP is apparently prohibitively expensive for the single-component application.

It should be noted that high-voltage ESP units are normally applied to highly concentrated emissions, whereas two-stage, low-voltage units are used for dilute liquid aerosols such as oil smokes and general air conditioning units. It was realized that the low-voltage units might be more applicable to the tunnel particulate problem, but these units cannot be used on solids, without washing adaptation. Further, the largest-capacity two-stage unit for which cost data are available is 100,000 ACFM, and the installed cost of this unit is about \$330,000, as against \$190,000 for the high-voltage ESP unit of the same capacity. Therefore, the cost situation for the two-stage low-voltage precipitator is even more negative than for the ESP unit calculated in detail above, and this unit was not reviewed further.

Based on data provided by Western Precipitation Division of Joy Manufacturing Company, a precipitator volume of 16,680 cubic feet was estimated as necessary to handle the requirement of 250,000 ACFM at a 5 ft/sec linear velocity.

While a number of different types of wet collectors can be used for particulate collection, a preliminary survey of normal capacity ranges and head losses indicate the spray chamber to be the lowest head-loss, highest through-put device. Basically, because of the humidification problem, wet collection devices of any sort cannot be used within a tunnel for treatment of air which will be re-introduced into the tunnel. All wet scrubbing devices inherently contain an initial adiabatic gas saturation zone, and this evaporation mechanism actually hinders particulate collection because of the diffusion of water vapor away from the liquid drops or surface (sweep diffusion). Because of the saturation phenomenon associated with wet contactors, these units can be employed only for exhaust air treating, and cannot be considered for control of the in-tunnel atmosphere. However, many tunnels have spray chambers to protect the exhaust fans in the event of tunnel fires, and it is of direct interest to estimate the capabilities of such present equipment for gross tunnel emission control. This present section is limited to the consideration of the application of spray chambers to particulate removal only.

Although there are several estimation techniques available for calculation of crossflow spray chamber requirements for particulate removal, the methods of Ranz and Wong[114] have been successfully employed previously for industrial design problems, and these were used to obtain a preliminary size estimate for spray chamber volumes. These calculations are given in detail in the Appendix II and the results are presented in summary form in Table 32. The required chamber holdup time depends on the spray rate ratio of water/air, the liquid droplet size, aerosol particle size and the required particulate removal efficiency. For the 500-micron spray drops, the required residence contact time falls off rapidly with the increase in aerosol particle size, at any given efficiency level. For the 90% removal level, the contact time decreases from 16.1 seconds for a 2-micron aerosol particle, to 1.75 seconds for a 5-micron particle. The corresponding volumetric chamber requirements are 67,000 ft^3 and 7,300 ft^3, respectively. For a decrease in efficiency from 90% to 75%, the volume requirements on a 5-micron particle basis changes from 7,300 ft^3 to 4,400 ft^3.

As is obvious from Table 32, the governing variable for particulate removal in a spray system is the size of the particulate. As was indicated earlier, more than 95% of the mass of automotive exhaust fumes is in the plus-1 micron size

TABLE 32

SPRAY HOLDUP TIME & CHAMBER VOLUME
AS FUNCTION OF DUST PARTICULATE SIZE

500-Micron Spray Droplets
20 Lbs./MCF Spray Rate

D_p, Aerosol Size Microns	N Impaction Efficiency	Holdup Time Required, Sec. (90% Efficiency)	Volume of Spray Chamber $ft.^3$	Holdup Time Required, Sec. (75% Efficiency)	Volume of Spray Chamber $ft.^3$
1	0	---	---	---	---
2	0.07	16.1	67,000	9.7	40,500
3	0.355	3.16	13,200	1.92	8,000
4	0.54	2.08	8,650	1.26	5,250
5	0.64	1.75	7,300	1.06	4,400

range. Further, a spray system tends to increase particle size by agglomeration, so that a degree of particle growth can be expected. Also, in the normal spray system, the liquid is colder than the gas, and a certain amount of condensation on the aerosol particulates will occur, increasing the particle size. The chamber sizes required for the removal of plus-3 micron particulates from 250,000 CFM of air in Table 32 are reasonable and, given the expected particle size distribution, the use of spray chambers for removal of particulates from tunnel exhaust air at good efficiency (75-90%) appears to be technically feasible.

Because water spray scrubbing was under consideration as a tunnel exhaust treatment technique, a detailed estimate was not attempted, and the preliminary costs were calculated under the assumptions and the data of HEW, AP-51, as outlined previously. Using the wet scrubber cost data for a 250,000 CFM unit:

Annual Capital Cost:

Purchase Cost =	$32,000
Installation Cost(@ 100%) =	$32,000
Total Installed Cost	=	$64,000
and Annual Capital Cost	=	(0.133)($64,000)
	=	$8,512

Annual Operating and Maintenance Cost, (G):

$$G = S(0.7457HK(Z + Qh/1980) + WHL + M)$$

where	Value
S = Design capacity, ACFM	250,000
H = Annual operating time, at 50%, hours/year	4,380
K = Power costs, $/kw-hr (typical)	0.011
Z = Contacting power, HP/ACFM (low)	0.0013
Q = Liquor circulation rate, gal/ACFM(low)	0.001
h = head required, ft of water (high)	60
W = Make-up water, gal/ACFM	0.0005

L = Water cost, \$/gal x 10^{-3}(typical) 0.50

M = Maintenance cost, \$/ACFM(low) 0.02

now $(Z + Qh/1980) = 0.00133$

and $WHL = (0.005)(4,380)(0.5 \times 10^{-3})$

$= 0.001096$

$G = (250,000)(0.7457)(4,380)(0.011)(0.00133)+(0.0211)$

= \$17,250

Total Annual Cost = \$8,510 + \$17,250

= \$25,760

The annual operating and maintenance costs are on the high side because of the use of generalized wet scrubber cost data. The spray chamber is the simplest device of all wet contacting units, but the absence of specific unit operating cost information prevents a more rigorous analysis. If more definitive costs are required, a reassessment of operating costs is recommended for a specific tunnel location and a localized cost structure.

Process Feasibility: Water Solubles

Inspection of Table 27 shows that the water-soluble pollutants include the oxygenated hydrocarbons, primarily formaldehyde and acrolein, nitrogen dioxide, sulfur dioxide and carbon dioxide. Other than the fact that the oxygenated hydrocarbons are eye irritants, the use of a wet scrubbing operation would not appear to be warranted for removal of these components at the concentration levels indicated. However, properly-designed spray chambers have the capability of removal of carcinogens of the benzo-(a)-pyrene type[115] and they have also been found to be fairly effective in the removal of even rather insoluble gases[116]. The only valid basis for evaluation of wet scrubbing as an exhaust pollution control technique is experimental work on the pollution system representative of diluted automotive exhaust. For the present, feasibility may be only indicated, not calculated.

The primary indicators of the feasibility of wet scrubber or spray chamber application to tunnel exhaust cleaning are the size of the unit to be required, and its probable efficiency. Spray chamber capacities and efficiencies were investigated by Pigford[80], and mass gas flow rates of 2000 lbs/hr/ft^2 were reported as being achievable in cyclonic

entrance units with central core sprays, or in countercurrent or crosscurrent contactors with good mist elimination. For air, the base ventilation flow rate of 15 x 10^6 CFH would require a cross-sectional flow area of 562 sq ft to match the 2000 lb/hr/ft^2 mass rate. This area is equivalent to a vessel diameter of about 27 ft, which is roughly the size of a two-lane tunnel. However, units of this size are not uncommon in industry, and since it could be built external to the tunnel proper, the diameter needed does not appear impractical. Again, the benefits of exhaust pollutant removal require further definition both on a health and nuisance basis.

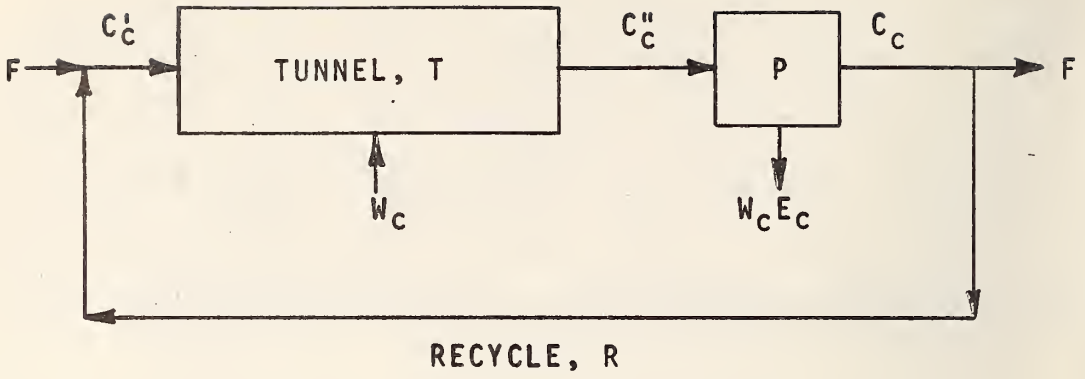
The extensive data of Pigford[80] on spray chamber absorption show that from 1 to 3 transfer units are available in such equipment, depending on the design. This contact efficiency is adequate for soluble gases with favorable equilibrium relationships at the low concentration levels. Calculations indicate that all of the oxygenated hydrocarbons can be removed by wet scrubbing, as can a significant portion of the nitrogen and sulfur oxides. The extent of removal of the latter compounds, as well as that of additional material, depends on the water/gas ratio, the liquid temperature, and the degree of water recycle. Experimental data are required to define the specific pollutant removal efficiencies as a function of these parameters, and the present feasibility must be regarded as uncertain.

The economics of spray scrubbing have been reviewed in the previous section.

General Feasibility: Recycle & Compartmentalization

One of the original project assignments was the investigation of the possibility of utilizing recycle operations, in which the treated tunnel air would be cycled back, in whole or part, through the tunnel or a section of the tunnel. Fundamentally, the problem is simply one of assessing the accumulation and buildup of contaminants during recycling. While a theoretical treatment is possible, it was found much more instructive to utilize the 250,000 CFM tunnel ventilation model, and the 2260 CFH CO generation rate, and investigate the effect of different recycle operating modes on CO concentration levels, as an illustrative example.

Assuming now a tunnel, or tunnel section, T, followed by a treatment process, P, for the removal of CO at an efficiency of E_c:



where

F = fresh air rate, CFH

R = recycle air rate, CFH

Wc = rate of CO generation in T, CFH

C_C = concentration of CO leaving process, P, ppm

C_C' = concentration of CO entering tunnel, T, ppm

C_C'' = concentration of CO leaving tunnel, T, ppm

Assuming there is no CO content in fresh ambient air, and taking a process efficiency of 90%:

$$R + F = 15 \times 10^6 \text{ CFH}$$

Let:

$x = R/F$ = Recycle ratio

Substituting in the above equation:

$$F = \frac{15 \times 10^6}{(1 + x)}$$

At steady-state conditions, CO input = CO output from system, so:

$$FC_C = W_C (1 - E_C)$$

and

$$FC_C = 2260 (1 - 0.9)$$

$$C_C = 226/F$$

Now from CO balance around the bleed point:

$$(R + F)\, C_c' + W_c\,(1 - E_c) = (R + F)\, C_c$$

and $$(C_c - C_c') = \frac{226}{15 \times 10^6} = 15.1 \text{ ppm}$$

Assuming values of the recycle ratio, x, the concentrations of CO leaving the tunnel can now be calculated. This has been done for values of x from 0.5 to 4, and the results are tabulated in Table 33. Without any recycle air, the concentration of CO leaving the tunnel is the base value of 150 ppm, which is simply the generation rate (2260 CFH) divided by the tunnel ventilation rate of 15×10^6 CFH. It is obvious that any and all values of recycle serves to increase the CO concentration of tunnel air above the base value without recycle. Further, even if the process removal efficiency is increased to 100%, the tunnel CO concentration then only becomes equal to the base 150 ppm value. For any process removal efficiency of less than 100%, the tunnel concentration must increase above the base value of 150 ppm CO with any finite value for recycle. If there were no piston effect, it must be concluded that recycle air operation in tunnel ventilation is completely impractical, and would only result in higher pollutant concentrations than would be the case without recycle. However, since a piston effect does exist, and is in fact impossible to eliminate, recycle could prove to be a feasible although highly expensive process.

A glance at the model used for the above calculation will show that it applies equally well to internal recycle operations between sections of a tunnel as well as to a complete tunnel system. Thus, no matter where the recycle is placed, the pollutant concentration increase will occur. An examination of the assumptions made in the derivation of the data of Table 33 show that these are not limiting, and the above conclusions are general for any pollutant generated at any rate.

In the latter part of the feasibility program, it was requested that the possibility of compartmentalization of sectionalization of tunnel air treatment be examined. One of the underlying assumptions of the control processes previously considered in this report was that they would have to operate with a (polluted) air intake intermediate in tunnel location. Because it would make little sense for this air intake to be located at the normal point of maximum pollutant concentration (too late) or at the inlet (too soon), it was obvious that the location would be determined by pollutant concentration gradient with distance, and the desired limiting value. However, in any event, the basic assumption of intake location was one of a two-section compartmentalization of the tunnel. The two-section

TABLE 33

INFLUENCE OF RECYCLE ON CO CONCENTRATION

Total Air Flow = 15×10^6 CFH

CO Generation = 2260 CFH

Recycle Ratio X = R/F	F Makeup Air Rate CFH x 10^6	R Recycle Rate CFH x 10^6	Cc CO Concentration leaving P, ppm	Cc CO Concentration entering T, ppm	Cc CO Concentration leaving T, ppm
0	15	0	---	0	150
0.5	10	5	22.6	7.5	157.5
1	7.5	7.5	30.8	15.7	165.7
2	5	10	45.2	30.1	180.1
3	3.75	11.25	60.7	45.7	195.7
4	3	12	75.3	60.2	210.2

compartmentalization requires the use of one control process installation, and generalizing, the breaking of the tunnel into n treating sections requires the use of (n-1) process units.

The practicality of tunnel compartmentalization beyond (n-=2) is primarily an economic rather than a technical problem. If it is assumed that sectionalization is complete, and that therefore each process unit between compartments will have to treat the entire tunnel air flow, then the two-compartment process costs already calculated may be simply multiplied by (n-1) to obtain the cost of this expansion. Inasmuch as the two-compartment costs of the individual control processes are already greatly in excess of augmented tunnel ventilation fan costs, multiplying these costs by an integer of 2 or greater will only emphasize the economic disadvantages of secondary pollution control techniques. If it is assumed that only partial compartmentalization is contemplated with air bypass, so as to avoid the necessity of repeated processing of the entire tunnel air flow, a complete re-evaluation of the costs is required. However, inspection of the cost-capacity curves in HEW, AP-51 shows the capital costs of control equipment vary with capacity to an exponential power of less than 1.0. Thus, the total cost of say, two 125,000 CFM control units, will exceed that of a single 250,000 CFM piece of equipment, so that the economics of compartmentalization with partial intermediate processing is apparently more unfavorable than total single-stage treatment.

Conclusions of Alternative Control Technologies

The estimated annual costs for the various pollution control processes evaluated in this study are summarized in Table 34. This tabulation permits a cost comparison of the alternate control techniques, and in purely economic terms, it appears that augmentation of tunnel ventilation is the most attractive control measure. This would be particularly true for existing low head-loss tunnel ventilation systems, in the range of 1" to 2" W.G. However, for the higher initial head-loss tunnel systems above 2" W.G. the increase in annual power costs required for significant flow augmentation would bring the total cost of this method above that of catalytic oxidation or spray scrubbing.

As indicated in Table 34, when feasibility factors are added to the economic considerations, then there appears to be no secondary pollution control technique with the cost-effectiveness capability of ventilation blower addition or substitution at the present time. However, the desirability of additional development work on catalytic oxidation and spray scrubbing is definitely indicated by the data of Table 34, and it is recommended that additional laboratory and pilot work

TABLE 34

PROCESS COST AND FEASIBILITY SUMMARY

250,000 CFM Ventilation Rate Tunnel

	Pollutant	Feasibility	Annual Capital Costs, $	Annual Operating Costs, $	Total Annual Costs, $
Augmented Ventilation	All	Depends on			
1" P		initial system	4,980	4,095	9,075
3" P		design and	6,250	12,103	18,353
4" P		head	6,680	16,285	22,965
Catalytic Oxidation	(CO & HC)	Probable	19,189	4,095[a]	23,284
Carbon Adsorption	(HC)	Probable	23,600	11,903	35,503
Electrostatic Precipitation	Part.	Doubtful	40,698	13,130	53,828
Spray Chamber	Part.	Exhaust only	8,512	17,250	25,760

(a) Blower operating cost, 1" W.G.

on these operations be undertaken. Based on the process review and analyses carried out in this study, the following conclusions may be drawn:

1. Both exhaust source control and tunnel ventilation augmentation appear to be either more effective or more economical pollutant control strategies than secondary processing of vehicular tunnel atmospheres. Projections of exhaust emissions under presently-mandated standards and source controls and correcting for auto population age, indicates a reduction in average hydrocarbon emission from 660 ppm to 156 ppm in the period 1970-1980, and a corresponding reduction in average CO emission from 25,790 ppm to 6,120 ppm. Thus, the problem of tunnel atmosphere pollution appears to be one of decreasing severity, and secondary controls may not be required.

2. Tunnel ventilation augmentation appears to be economically and technically more attractive than any secondary pollution control process. Both catalytic oxidation, and carbon adsorption control operations are fixed-bed units requiring supplemental blower head additions to force air through the process. This creates the anomaly that tunnel ventilation augmentation must be used in conjunction with any fixed-bed control process, but the potential direct ventilation increase benefits are nullified by the process use.

3. Ambient temperature catalytic oxidation appears to be potentially the most attractive secondary control process. Further development is required to assess its capability for CO and hydrocarbon removal at the low concentrations existing in tunnel air, and to yield more complete data for design.

4. Spray scrubbing has apparent application to the control of gross tunnel exhaust emissions, and if localized control is necessary or desirable, further study of the full capability of this operation should be undertaken. This and other wet scrubbing methods are not suitable for in-tunnel use because of the accompanying gas saturation and the resultant in-tunnel fog possibilities.

5. Investigation of conventional electrostatic precipitation for the removal of the particulates from tunnel air showed this process to be of doubtful feasibility because of the extremely low particle concentration. Further, cost studies showed it to be the most expensive control method of those reviewed.

6. A study of recycle operations shows that any degree of processed air recycle around the tunnel or any part of the tunnel will yield higher in-tunnel pollutant concentration levels than would be the case for once-through air ventilation. However, the injection of fresh air into a tunnel by the piston effect could compensate for the build-up of pollutants.

Selection of Control Techniques to be Evaluated

General Discussion - A significant amount of work has been and is being done on pollution control techniques and devices for industrial operations, power plants and automobile exhaust systems. In these types of pollutant sources, the effluent gas stream is at an elevated temperature and the concentration of pollutants is high. As an example, motor vehicle exhaust emission concentration ranges to 3% CO (30,000 ppm) and 0.5% H-C (5000 ppm) and temperatures range from 150°F to 1500°F. Conversely, tunnel atmospheres generally range to maximum pollution concentrations of 250 ppm CO and 50 ppm H-C, with near ambient temperatures ranging from 20°F to 90°F. It is obvious from this comparison that many of the control techniques which have been developed recently are not necessarily applicable to tunnel pollution control.

The constraints imposed by a tunnel atmosphere dictates and limits the types of purification processes which can be used. These constraints include:

1. Relatively low ambient temperature
2. Relatively low pollutant concentration levels
3. High throughput rates
4. Low exit concentrations.

Additonal constraints are imposed depending upon whether the tunnel atmosphere is to be recycled (either completely or in a compartmentalized fashion) or merely exhausted to the atmosphere. In recycle, consideration must be given to cooling, CO_2 removal, water removal and perhaps oxygen make-up. These constraints are not imposed where the air is to be purified prior to exhaust to the atmosphere.

On the basis of recommendations for allowable impurity limits in tunnels along with the current Environmental Protection Agency national air quality standards, removal systems for the following pollutants must be considered:

1. CO
2. H-C
3. $NO-NO_2$
4. Particulates

The EPA has also established limits for SO_2 and photochemical oxidants, but these do not appear to be problems in vehicular tunnels based on measurements which have been made.

Carbon Monoxide Removal Systems - A review of the literature revealed two potentially promising means of CO removal, based on temperature requirements and throughput rate. These two general classes of catalytic oxidizers included manganese-copper oxide and transition metal oxides on activated carbon. A review by Cannon and Welling [58] indicated that 60% MnO_2-40% CuO completely oxidized a gas mixture containing 3% CO, 1% H_2, 0.1% gasoline, balance nitrogen at 25°C with a standard space velocity of 18,800 hr^{-1}. The other catalyst resulted in 90% oxidation of CO at 120°C at a space velocity of 200 hr^{-1}. However, at space velocities of 4800 hr^{-1} only 50% conversion of CO was attained. Of these two catalysts, the MnO_2-CuO catalyst appeared to be more promising on the basis of both temperature and throughput rate and therefore was selected for small scale evaluation of its effectiveness on diluted auto exhaust.

Hydrocarbons - Catalytic oxidation or thermal afterburning both can be used to oxidize hydrocarbons. These methods must be essentially 100% efficient otherwise the partially oxidized hydrocarbons may be more toxic and/or noxious than the initial hydrocarbon. To assure 100% conversion, high temperatures must be used, hence oxidation was felt to be an inappropriate means of hydrocarbon removal. Activated carbon appeared to be the most promising technique for removal of hydrocarbons. Activated carbon will remove the heavier and most of the partially oxidized hydrocarbons at ambient temperatures. Activated carbon will also remove NO_2, another of the impurities selected for consideration for removal from tunnel atmospheres. An attractive feature of activated carbon is that it can be regenerated, preferably with steam, and therefore the maintenance or replacement problems are minimized. Because of the promising outlook for activated carbon for removal of both hydrocarbon and NO_2, it was selected for study on diluted automobile exhaust.

Oxides of Nitrogen - As stated earlier, activated carbon will remove NO_2. However, it is ineffective for removal of NO, which accounts for ~80% of the total oxides of nitrogen emitted from auto exhaust. Thermodynamically, the conversion of NO into O_2 and N_2 is favorable, but no catalysts have been found which will effect this decomposition at reasonable rates or temperatures. Unfortunately, catalytic removal of NO_x from gas streams requires a reducing atmosphere, a condition which does not exist in polluted tunnel air. Conversely, proprietary information exists which indicates that NO can be

catalytically oxidized to the nitrate form. It has also been reported that NO can be oxidized to NO_2, which could be sorbed on activated carbon, but the process requires a gas dewpoint of -60°F. The possibility of liquid scrubbing appeared to be of questionable applicability in light of the NO concentrations in tunnel atmospheres. In summary, the removal of NO seemed to be the major problem of tunnel pollutant purification. The DOT Technical Officer in discussion with Marbon Chemical Division of Borg-Warner Corporation suggested that Purafil, a chemisorbent impregnated with $KMnO_4$ might remove NO_x from the atmosphere. It should be noted that this material functions by chemical reaction rather than catalytic action and would therefore have to be replaced periodically. However, since other methods seemed impractical and since MSAR had a supply of this material on hand, it was decided that Purafil would be evaluated on diluted auto exhaust.

Particulates - Typical means of removal of particulates from gas streams include mechanical separators such as cyclones, wet collectors, electrostatic precipitation and filtration. The efficiency of each of these methods depends upon such factors as particle size, density, concentration and electrical resistivity as well as moisture content of the gas and physio-chemical characteristics of the gas. Cyclone separators are not particularly efficient for the size range (<1 μ to 5 μ) of particles in tunnels and in general require large energy inputs with attendent high pressure drops. With the present state-of-the-art of wet collectors, efficiencies at the anticipated particulate levels and particle sizes in tunnels would likely be quite low. Electrostatic precipitation and filtration may be applicable to the problem. However, since manufacturer's data are available for these types of particulate removal systems as well as for wet scrubbing systems, it was decided that no laboratory work on particulate removal would be performed.

Purification Test System

Figure 31 is a schematic diagram of a 4300 ft^3 chamber at MSAR. The chamber is leak-tight and is made of carbon steel with the inside walls coated with aluminum paint. The chamber is fitted with an air blower with a capacity of 80 cfm. Minor modification to the chamber included installation of an inlet port for injection of auto exhaust.

Major modifications to the chamber involved installation of monitoring equipment, test beds and a gas stream heater (Fig. 31). The monitors which were used included:

① Temperature
② Pressure
③ Relative humidity
④ Carbon monoxide
⑤ Total hydrocarbons
⑥ Carbon dioxide
⑦ Oxygen
⑧ Particulates
⑨ Nitrogen oxides
⑩ Air sample for GC

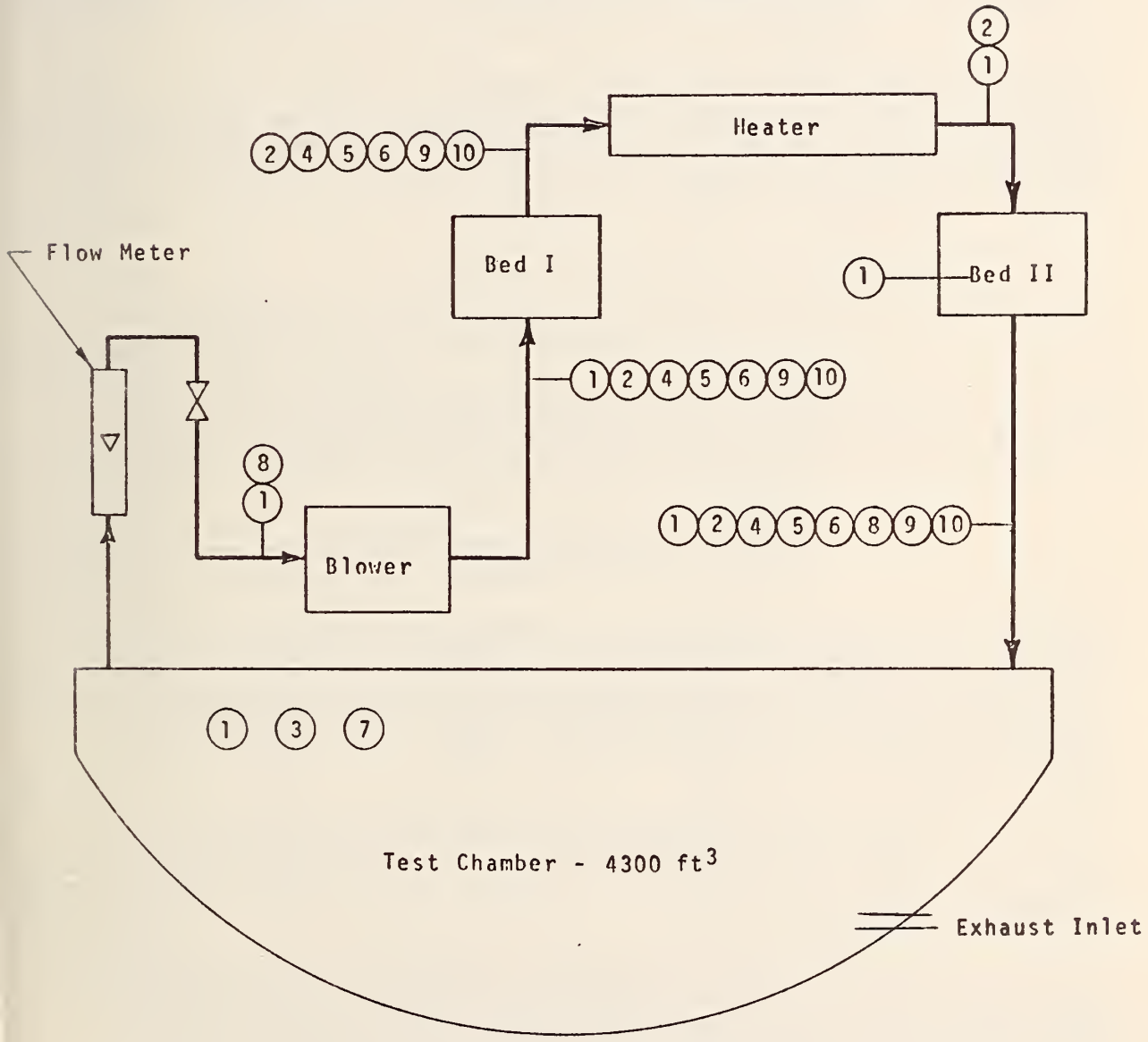


FIGURE 31 - AUTOMOTIVE EXHAUST PURIFICATION TEST CHAMBER

Impurity	Instrument	Range
CO	MSA Lira Model 200 (IR)	0-300; 0-500 ppm Full Scale
Total H-C	MSA Total H-C Analyzer	0-5; 0-15; 0-30; 0-60 ppm
CO_2	MSA Lira Model 200	0-0.5%
O_2	Biomarine OM-300 Analyzer	0-100%
H_2O	Motometer RH Indicator	0-100%
Particulates	Royco Model 200 PC	0-64 μ to 5.0 μ; 100 particles/cc
$NO-NO_2$	Wet chemical; Saltzman Method	0.01-10 ppm

A fan was installed inside the chamber to assure rapid mixing of the contaminated gas. In most runs, the auto exhaust was provided by a 1963 Chevrolet Impala with 103,000 miles on it; the source of auto exhaust for the first two runs was a 1967 Chevelle with 33,000 miles on it.

A typical run was as follows:

1. Run automobile engine for 1.5 min; car in drive; accelerator slightly depressed; brakes on.
2. Circulate contaminated air for 5 min to assure complete mixing within the chamber.
3. Turn on blower and set to desired flow rate.
4. Collect monitor readings at various intervals depending upon the type of removal system and rate of removal.

The first run was a blank run to determine whether the test chamber and associated equipment resulted in change in concentration of any of the contaminants during circulation without any purification system on line. The results indicated no change in concentration with time except for the particulates.

Table 35 is a summary of the runs which were made. Results of each run are discussed in the following subsections.

Run No. 1 - Blank

Run No. 1 was a blank run although a fiber glass mat was placed in one of the purification canisters to provide a pressure drop across the system. The vehicle used for the pollutant source was a 1967 Chevelle and was run at idle for 5 min. Small differences can be seen in the CO inlet (300 ppm) versus the CO outlet (285 ppm) and the HC inlet (78 ppm)

TABLE 35 - SUMMARY OF PURIFICATION SYSTEMS

Run No.	Type of Purification	Bed Wt. lbs	Bed Temp. °F	Space Velocity hr^{-1}	Residence Time sec.	Flow CFM	Press. Drop in Water	Vehicle Run Time Min.	CO ppm In	CO ppm Out	H-C ppm In	H-C ppm Out	NO ppm In	NO ppm Out	NO_2 ppm In	NO_2 ppm Out	CO_2 % In	CO_2 % Out	RH
1	Blank	NA	NA	NA	NA	82	3.3	5	300	285	78	61	0.051	0.048	0.029	0.011	0.10	0.10	85
2	Hopcalite (Cold)	12.0	92	17,100	0.21	84	3.6	2.5	280	215	43	41	0.14	0.006	0.069	0.08	0.12	0.12	52
		12.0	92	12,100	0.30	60	2.0	---	205	190	41	41	0.04	0.02	0.10	0.12	0.12	0.12	52
3	Activated Carbon	8.0	92	17,100	0.21	84	3.0	2.5	300+	300+	84	22	4.03	4.47	1.38	0	0.24	0.24	90
		8.0	92	4,100	0.88	20	3.0	---	300+	300+	60	20	3.16	3.68	1.05	0	0.23	0.23	90
		8.0	92	8,200	0.44	40	---	---	300+	300+	60	20	----	----	----	----	0.23	0.23	90
4	Purafil	12.0	90	17,100	0.21	84	2.0	1.5	357	320	56	47	0.93	0.30	0.44	1.26	0.11	0.11	85
		12.0	93	8,500	0.42	42	0.5	---	320	320	48	38	0.26	0.10	0.63	0.57	0.11	0.11	85
	20 hr total	12.0	95	17,100	0.21	84	2.0	---	270	270	25	24	0.00	0.00	0.018	0.018	0.10	0.10	85
5	Hopcalite (Hot)	1.0	95	9,500	0.04	38	18.2	1.5	287	230	60	53	1.55	0.89	0.14	2.49	0.13	0.13	65
	700 watts input	1.0	96	4,700	0.08	19	8.8	---	235	223	59	55	----	----	----	----	0.13	-.13	64
	1650 watts input	1.0	175	4,700	0.08	19	10.7	---	220	30	54	38	1.43	0.15	0.30	0.66	-.13	0.16	63
		1.0	240	4,700	0.08	19	12.0	---	117	3	50	29	1.48	0.69	0.44	0.22	0.14	0.16	61
6	Hopcalite / Silica gel	2.0 / 1.0	90	4,700	0.08	19	11.9	1.5	500	480	61	61	0.56	0.52	0.12	0.23	0.09	0.08	89
7	Hopcalite	0.25	167	18,800	0.02	20	3.6	1.5	203	147	50	47	----	----	----	----	0.10	0.10	86
	1635 watts		275	18,800	0.02	20	6.0		147	20	43	30	0.91	1.01	0.20	0.02	0.11	0.12	86
	1635 watts		227	28,200	0.015	30	6.4		141	63	42	36	----	----	----	----	0.11	0.12	85
	2620 watts		260	28,200	0.015	30	6.4		124	38	31	29	0.99	1.09	0.15	0.03	0.11	0.12	85
	1080 watts		276	9,400	0.04	10	1.8		102	8	38	24	0.89	0.61	0.13	0.02	0.10	0.11	84
8	Particulate Filter 65% efficiency		Results void; face velocity too high																
9	Particulate Filter 99.5% efficiency		Results void; face velocity too high																
10	60% MnO_2 + 40% CuO	1	86	2,350	0.16	10	3.3	1.5	349	346	53	53	0.39	0.51	0.04	0.06	0.11	0.11	
	750 watts		201	2,350	0.16	10	4.0		329	297	52	52	0.41	0.89	0.03	0.00	0.12	0.12	
	1700 watts		247	2,350	0.16	10	4.4		325	297	53	52	0.47	0.94	0.02	0.00	0.12	0.12	
11	Charcoal + Hopcalite	1	94	11,750	0.03	50	5.6		487	474/468	50	23/20	0.36	0.22/0.22	0.14	0.04/0.11	0.10	0.10/0.10	
	750 watts		134	11,750	0.03	50	5.6		436	426/414	28	18/17	----	----	----	----	0.10	0.10/0.10	
	2620 watts		265	11,750	0.03	50	5.9		356	351/132	23	17/17	----	----	----	----	0.10	0.10/0.12	
	2620 watts		261	4,700	0.08	20	2.0		318	318/40	22	17/16	----	----	----	----	0.10	0.10/0.12	
	2700 watts		311	2,350	0.16	10	2.0		293	293/17	22	15/15	0.16	0.10/0.22	0.08	0.00/0.02	0.10	0.10/0.12	
12	Charcoal + Moisture Tolerant Hopcalite	1 / 2	93	4,700	0.08	20	2.6	1.5	445	445/439	48	23/23	0.52	0.28/0.11	0.09	0.00/0.41	0.1	0.1/0.1	68
	1700 watts		280	4,700	0.08	20	2.9		400	395/0	40	23/22	0.33	0.21/0.02	0.09	0.00/0.02	0.10	0.10/0.14	
	1100 watts		240	4,700	0.08	20	3.9		290	290/0	32	21/20	----	----	----	----	0.12	0.12/0.14	
	600 watts		185	4,700	0.08	20	3.2		248	248/8	31	21/20	0.20	0.13/0.03	0.04	0.00/0.02	0.12	0.12/0.14	

versus the HC outlet (61 ppm). This could be attributed to physical sorption on the fiber glass mat. A slight reduction in NO and a large reduction in NO_2 concentration was also noted, but problems existed with the NO-NO_2 analyses at that time, so these differences may not be real. The difference in the concentration of particulates greater than 1 micron, 550/cc versus 60/cc was probably due to the filtration effect of the fiber glass mat.

Run No. 2 - Cold Hopcalite

Initially, it was intended to use the 60% MnO_2-40% CuO catalyst reported by Cannon and Welling to be effective for CO at 25°C (77°F). No commercial source of this catalyst could be located so Hopcalite, a coprecipitated 70% MnO_2-30% CuO catalyst was substituted in its place. The bed was run at 92°F. Again, a 1967 Chevelle was used at idle, but idle time was 2.5 min. At a space velocity of 17,100 hr^{-1} (residence time of 0.21 sec), no significant reduction was observed for CO or HC. The oxides of nitrogen did appear to undergo oxidation in that the inlet NO was 0.14 ppm and the outlet NO was 0.006 ppm. This would indicate oxidation of NO to NO_2. Further verification of this is the fact that the outlet NO_2 (0.08 ppm) was higher than the inlet NO_2 (0.069 ppm). At a space velocity of 12,100 hr^{-1} (residence time of 0.30 sec), the CO and HC were not changed, but again it appeared that NO was being partially oxidized to NO_2.

Run No. 3 - Activated Carbon

In this run, as in all subsequent runs, a 1963 Chevrolet Impala was used as a pollutant source and was run under load conditions. Coconut based activated charcoal was used as the purification media. The CO concentration was off scale, but it is known that charcoal is ineffective for CO removal. At a space velocity of 17,100 hr^{-1} (RT = 0.21 sec), a significant reduction was observed in the H-C level and the NO_2 level. The H-C concentration was reduced from 84 ppm to 22 ppm (74% removal) and the NO_2 concentration was reduced from 1.38 ppm to zero ppm. The stream was tested upstream and downstream of the test bed for odor. The upstream odor was typical of the odors in tunnels while the downstream was odorless. Figure 32 is a chromatogram of an upstream and downstream sample showing that the heavy hydrocarbons (which are the more toxic and more odorous) had been removed. Additional tests at space velocities of 8,200 (RT = 0.44 sec) and 4,100 (RT = 0.88 sec) were made on the same pollutant charge. Again a major fraction of the hydrocarbons, 67% and 100% of the NO_2 was removed. The apparent reduced removal rate of hydrocarbons at these lower space velocities is due only to the fact that a portion of the heavier hydrocarbons had been

Chromatograph Hewlett Packard Model 5750 - dual column.

Columns - 6' x 1/8" stainless steel 10% UC-W98

Carrier gas - Helium 40 cc/min

Temperature - 30°C temp. program to 230°C at 20°C/min

Sample - ~230 cc of air. Hydrocarbons trapped on 12" x 1/8" stainless steel pre-column at -197°C packed with 45-60 mesh Chromosorb P

Detectors - Flame Ionization

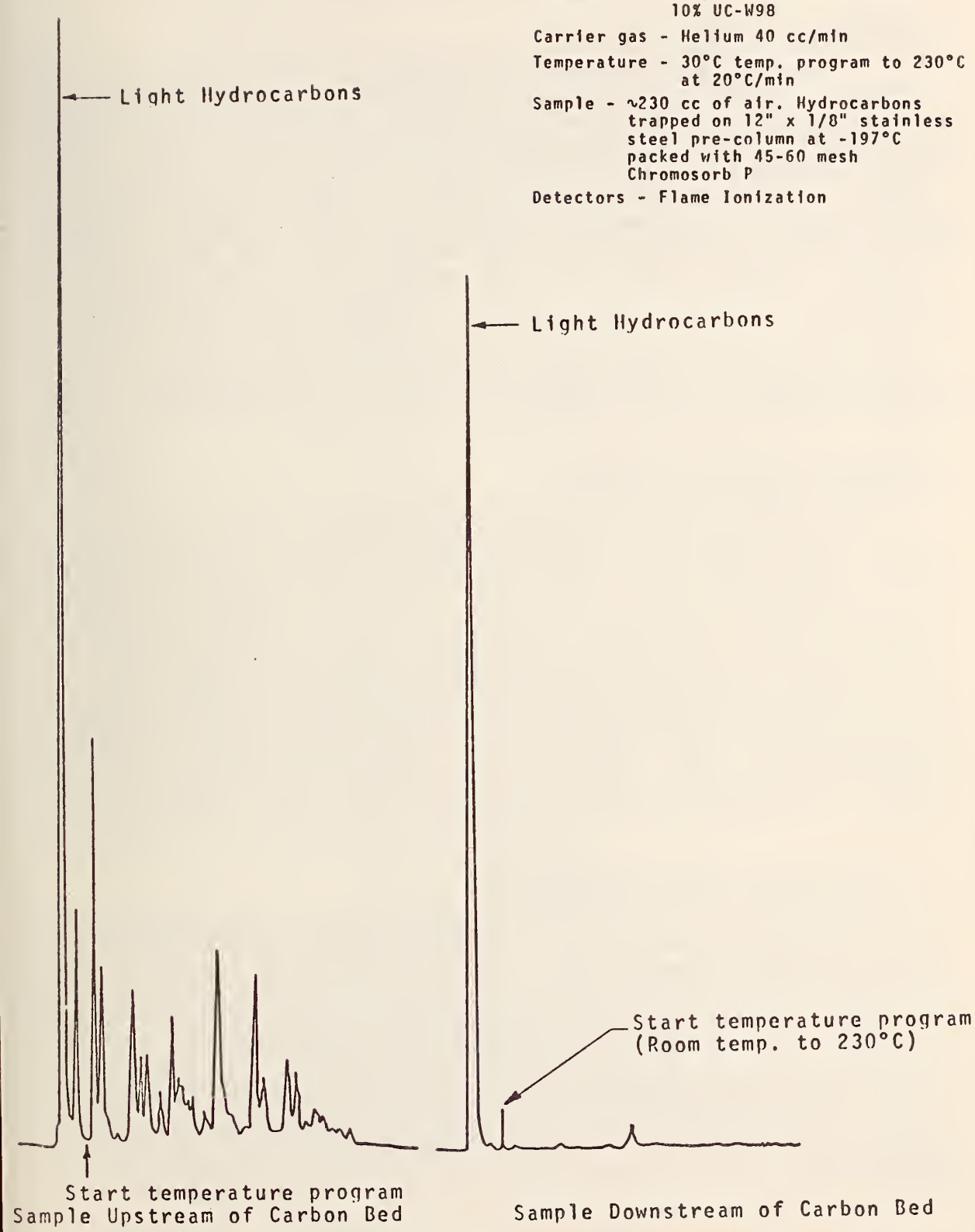

Light Hydrocarbons
Light Hydrocarbons
Start temperature program (Room temp. to 230°C)
Start temperature program
Sample Upstream of Carbon Bed
Sample Downstream of Carbon Bed

FIGURE 32 - REMOVAL OF HYDROCARBONS BY ACTIVATED CARBON

removed during the earlier part of the test thus increasing the ratio of light to heavy hydrocarbons.

Run No. 4 - Purafil

Purafil acts as a chemisorbent using $KMnO_4$ on a substrate of activated alumina. Purafil had no effect on the CO concentration but did reduce part of the hydrocarbon fraction as well as NO. At a space velocity of 17,100 hr^{-1} (RT = 0.21 sec) hydrocarbons were reduced by 18% and NO was reduced by 68%. At a space velocity of 8,500 hr^{-1} (RT = 0.42 sec) hydrocarbons were reduced by 21% and NO was reduced by 61%. The system was allowed to run overnight and the following morning, after a total run time of 20 hrs, the NO concentration had been reduced to zero and the NO_2 concentration was down to 0.018. After 20 hrs of operation, the Purafil did not appear to be removing any hydrocarbons, indicating that those hydrocarbons which are reactive with Purafil had been removed. Total reduction in hydrocarbon content was 57%.

Run No. 5 - Hot Hopcalite

This run was made with hot Hopcalite with the efficiency measured at various temperatures. At 95°F, a small reduction in CO (20%) and HC (13%) was observed, while NO was reduced by 43%. At 175°F, the CO was reduced by 86% and the hydrocarbons were reduced by 30%. The NO was reduced by 90%. At 240°F, the CO was nearly completely removed (97% removal) and the hydrocarbons were reduced by 42%. The behavior of the oxides of nitrogen at this temperature is difficult to explain since NO removal did not seem to be as efficient. However, the removal of NO_2 was observed for the first time indicating possible oxidation to the nitrate. It should be noted that the significant reduction in CO and HC resulted in an increase of CO_2 from 0.13% to 0.16%.

Run No. 6 - Silica Gel-Hopcalite

In this run, a silica gel bed was installed upstream of the Hopcalite bed in hopes that Hopcalite would be effective at ambient temperature if the stream were free of moisture. No significant improvement was noted in the removal of CO, HC or NO/NO_2. More effective drying agents might be considered, but for a system to be economical, the dryer must be regenerable. Those dryers which can be used only once and then discarded would increase both the replacement and maintenance costs. Of course, these costs have to be weighed against the cost of heating the air stream to ∿225°F, in the case of Hopcalite.

Run No. 7 - Hopcalite

This run was made with a 0.25 pound Hopcalite bed as opposed to the 1.0 pound beds used in earlier runs. At identical flow rates, the residence time was reduced by a factor of 4 while the space velocity was increased by a factor of 4. At a space velocity of 4,700 hr^{-1} and a residence time of 0.08 seconds used in earlier runs, the exit concentration CO was <1.5% (3 ppm) of the inlet concentration (117 ppm); this was accomplished at a temperature of 240°F. In this run, with a lower residence time and a higher space velocity, the CO was reduced by only 86%.

Runs 8 and 9 - Filter Media

These two runs were made with particulate filter media with efficiencies of 67% and 99% for 0.3 micron particles. The results from these two runs were considered unreliable because of the high face velocity at the filter, and the face velocity could not be reduced due to the performance characteristics of the air blower. Therefore, manufacturers data will have to be used for prediction of filter performance. Inquiries were sent to manufacturers of electrostatic precipitators, also.

Run No. 10 - MnO_2-CuO

This run was made using an admixture of 60% MnO and 40% CuO as described by Cannon and Welling. The two materials were mixed, about 10% water was added and the moist mix was pressed into a solid cake. The cake was dried and then sieved to 4-8 mesh granule size. The test showed little activity of the catalyst for CO.

Run No. 11 - Charcoal Plus Hopcalite

This run was made to determine the overall performance of two selected methods of tunnel air purification. The charcoal bed was located upstream of the Hopcalite bed, but in actual practice, it would be more sensible to locate the charcoal bed downstream of the Hopcalite bed since NO is converted to NO_2 in the Hopcalite bed. However, since no cooling was provided for the Hopcalite bed outlet stream, the optimum configuration could not be used in the test system. At 311°F, the CO was reduced by greater than 90% and the charcoal removed essentially 100% of the NO_2. The charcoal also removed a fraction of the hydrocarbons; gas chromatographic analyses indicated that the heavy hydrocarbons were removed.

Run No. 12 - Charcoal Plus Moisture Tolerant Hopcalite

This run was made with moisture tolerant Hopcalite since it is less susceptible to powdering than standard Hopcalite, thus providing a lower pressure drop across the system. Information was acquired during this run on the effect of temperature on CO removal and the results are shown in Figure 33. These results indicate that at a space velocity of 9400 hr^{-1}, a residence time of 0.04 sec and a temperature of 225°F, complete removal of CO can be expected.

Purification Systems for Tunnels

The laboratory work performed under this program demonstrated that the technology exists for purification of tunnel atmospheres. Application of these principals and methods to tunnel atmosphere purification requires a significant degree of system scale-up as well as an economic evaluation of systems required for handling large volumes of tunnel air. An earlier section of this report includes an evaluation of the cost requirements for such systems, but it should be kept in mind that the feasibility and economic studies were made prior to the laboratory studies. Because of this fact, some additional comments are warranted.

First, ambient temperature catalytic oxidation proved to be an unattainable goal. The laboratory studies indicated that a temperature of ∿225°F would be required for oxidation of CO using the best commercially available catalyst. As a result of this temperature requirement, an engineering design estimate of size and heat requirements for a 200,000 cfm unit with a regenerative heat exchanger was made. The results were as follows:

Heat requirements - 1.63×10^5 Btu/hr
No. of plates in heat exchanger - 200
Size of plates - 80 ft x 20 ft
Spacing between plates - 1/8 in.
Velocity through plates - 22 ft/sec
ΔP across heat exchanger - 4.7 in. H_2O

The second comment concerns the use of electrostatic precipitators to remove particulates. Inquiries were sent to a number of manufacturers of electrostatic precipitation units requesting performance characteristics and price. In regard to performance characteristics, the answers varied from - "it cannot be done by electrostatic precipitation" to "our units will reduce the particulate loading from 5 mg/m^3 down to 0.1 mg/m^3. Prices ranged from ∿$81,000 for a 50,000 cfm unit and $164,000 for a 250,000 cfm unit to $1,000,000 plus for a 250,000 cfm unit.

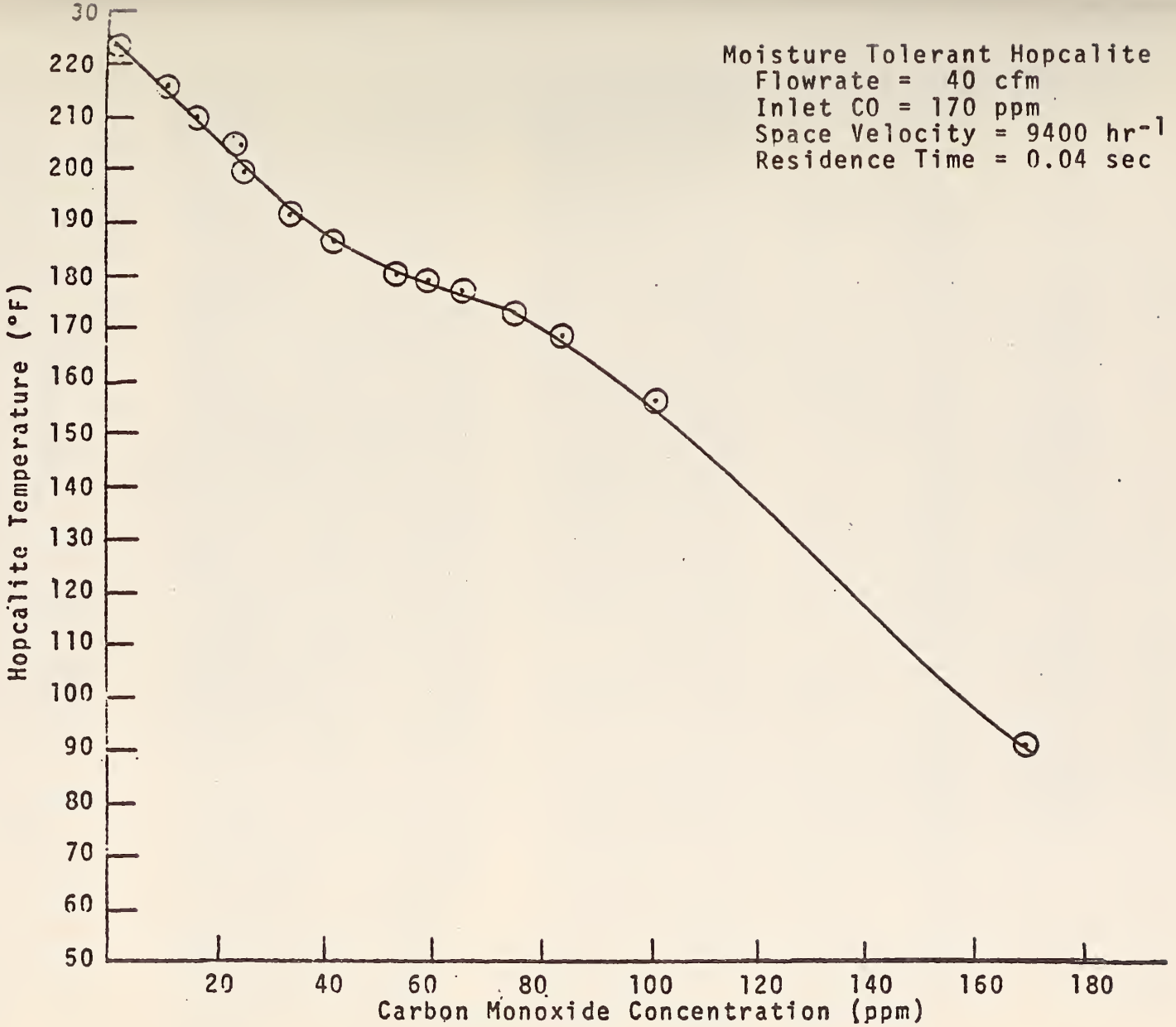


FIGURE 33 - EFFECT OF CATALYST TEMPERATURE ON CO CONCENTRATION

In conclusion, the technology exists for purification of vehicular tunnel atmospheres. The systems which were selected were those which required minimum replacement of the purification components. The three basic units of a purification system would include:

Particulates - electrostatic precipitation
CO - catalytic oxidation with Hopcalite at 225°F
(NO would be oxidized to NO_2)
NO_x and hydrocarbons - activated carbon

The electrostatic precipitator would be periodically cleaned by back washing; this could be done during an off-peak time. Activated carbon would require periodic regeneration with steam. The catalyst should have a lifetime of several years if properly protected from particulate contaminant, particularly lead. The electrostatic precipitator upstream of the catalyst bed should provide this protection.

The question arises as to the anticipated lifetimes of all the purification system components, as well as the regeneration frequency and maintenance requirements. These questions cannot be answered at this time. It is recommended that a small scale (perhaps 5000 cfm) system be fabricated and tested under actual tunnel conditions. The information acquired from such tests would reveal not only the removal efficiency of the system but also the lifetime of the components and the required maintenance and regeneration frequency.

It is apparent as a result of this study that the initial capital cost of a vehicular tunnel air purification system will be high. In addition to the capital cost, the power requirements will also be high due to the heating requirements and pressure drop across the system. For maintaining the quality of air within the tunnel, it would be significantly less expensive to increase the size of the ventilating air system. However, if in the future, tunnels must comply with EPA standards for emission from stationary sources, then purification systems on the exhaust stack will be required and systems to perform this treatment have been established as a result of this study.

TUNNEL INSTRUMENTATION

Historically, CO has been the only impurity which has been monitored on a continuous basis in vehicular tunnels in the United States; in Europe smoke meters have been used in conjunction with CO monitors in some tunnels. The read-out from the CO monitors have been used not only to indicate the CO concentration in the tunnel, but also to direct control room operators in selecting appropriate ventilation rates. Automatic ventilation control based on the signals from CO monitors have been used in a few tunnels, but none of the tunnels which we visited used the automatic control system.

The present emphasis on air quality and monitoring of atmospheric pollutants has accelerated the development of instrumentation capable of continuous monitoring of low level impurities in the atmosphere. Many of these instruments have combined classical, chemical and physical analytical techniques used in the laboratories with automated industrial process instrumentation. The resulting array of available instrumentation runs the gamut of sophisticated computerized mass spectrometers to simple rugged temperature indicators. The applicability of these instruments in monitoring the air quality of vehicular tunnels must be considered within the following constraints:

1. adequate sensitivity and specific response to the pollutants of interest,
2. operation and maintenance requirements,
3. capabilities of operating and maintenance personnel,
4. real-time data output,
5. reliable and reproducible operation.

Table 36 summarizes the types of instrumentation which are currently available for monitoring vehicular exhaust impurities. This table shows the principle of operation along with approximate cost ranges for each type of monitoring system.

Carbon Monoxide

Two general types of instruments are available for continuous monitoring of CO. These are the Hopcalite type and the non-dispersive infrared type of instrument. In general, the Hopcalite type has been used almost exclusively in tunnel monitoring applications. This instrument is rugged, inexpensive, simple and requires very little maintenance. The non-dispersive infrared type of instrument is more expensive

TABLE 36 - APPLICATION OF CONTINUOUS MONITORING INSTRUMENTS TO TUNNEL ATMOSPHERES

Constituent	Type of Instrument	Approximate* Price Range/Point	Remarks
Carbon Monoxide	catalytic combustion (Hopcalite)	350-700**	very rugged, simple, little maintenance required
	nondispersive infrared	2600**	specific, maintenance program required
Particulates (smoke)	light extinction	3000	open path sampling-self cleaning optics
	light scattering	6000	sophisticated electronics
	tape sampler	800	accumulative sample
Total Hydrocarbons	hydrogen flame ionization	2000**	non-specific detection, well established instrument
Oxides of Nitrogen	gas phase chemiluminescence	3000-4000	maintenance program required
Total Aldehydes	chemical colorimetric	3100-5000	requires chemical solutions
Carbon Dioxide	nondispersive infrared	1700-2600**	specific, maintenance program required
Oxygen	paramagnetic measurement	1500**	specific, rugged

*Note: These prices do not necessarily include the cost of pumps, plumbing, filters, cabinets, relays, etc.
**Add $700-1000 for recorder

and does require a more sophisticated type of maintenance program. However, the NDIR instrument has faster rise and response time characteristics:

	Rise Time (sec)	Initial Response Time (sec)
Hopcalite	100	20
NDIR	10	3

Furthermore, the NDIR instrument has lower sensitivity (2 ppm ± 2 ppm) compared to the Hopcalite instrument (10 ppm ± 5 ppm). Either instrument can be used to automatically control ventilation rates by feeding the signal output to an automatic fan control system.

For general monitoring of tunnel atmospheres, adopting a manned tunnel limit of 75 ppm and an unmanned tunnel limit of 500 ppm, the Hopcalite system should continue to satisfy the monitoring requirements. If in-tunnel purification is required, where the CO outlet from the purification system must be at or near zero, then the NDIR system should be used due to its lower limit of detection. The same reasoning holds true for the case of purifying the tunnel exhaust air where the outlet concentration set by EPA is less than 10 ppm CO.

Smoke or Haze

Smoke or haze in tunnels is a nuisance factor and with the increased use of diesel powered trucks and buses smoke has become a problem in tunnels. Because the CO/smoke ratio is different in gasoline powered vehicles versus diesel powered vehicles, no correlation can be made between the two contaminants. In conversations with control room operators at the tunnels which were visited, these personnel have learned to anticipate the increase in diesel traffic and the concommittant increase in smoke level and therefore increase the ventilation rate regardless of the CO monitor readings. An outstanding example of this is the evening rush hour diesel bus traffic from New York City.

No tunnels in the U.S. have installed smoke meters, but a few in Europe have[18] installed such instruments. Since there is essentially no information available on the performance of smoke meters in tunnels, no recommendations can be made on an acceptable smoke monitoring system. It is recommended that typical instruments be evaluated in a tunnel environment to determine the applicability of these instruments for monitoring smoke in tunnels and to determine the effects of the tunnel environment (fog, oil mist, particulates) on the performance characteristics and maintenance

requirements for such instruments.

Other Monitors

Hydrocarbons - Limits have been set for hydrocarbon levels in tunnels and the EPA has set air quality standards for hydrocarbon emissions from stationary sources. The standard instrumental method for total hydrocarbons employs the hydrogen flame ionization detection principal. Although this instrument does not provide readout for individual hydrocarbons, it is a well established instrument and is sensitive to 1 ppm of total hydrocarbons. Specificity can be attained by the use of chromatography but this should not be necessary for tunnel applications.

Nitrogen Oxides - Simple, reliable monitors for oxides of nitrogen at the levels anticipated have been developed recently. Most of the monitors currently on the market use a gas phase chemiluminescent reaction principle. Typical ranges for these instruments are 0-0.02 ppm, 0-0.2 ppm and 0-2 ppm. These are ranges which would be applicable for monitoring NO_x in vehicular tunnels. Some models can differentiate between the NO and NO_2 content of the atmosphere.

Total Aldehydes - Aldehyde monitors currently on the market are based on wet chemical techniques requiring chemical reactants to be used in the instrument. Although the instruments are automated frequent replacement of the reactants is required. Furthermore, current models are not specific for formaldehyde which accounts for the major fraction of aldehyde emissions from auto exhaust. The EPA is funding work on a formaldehyde monitor and an acceptable instrument may be available in the future.

Carbon Dioxide and Oxygen - Monitors for these constituents need only be considered if recycling of the tunnel atmosphere is used instead of ventilation. Carbon dioxide can be reliably measured using NDIR which is specific for CO_2. Oxygen monitors generally are based on the paramagnetic characteristics of O_2. Instruments are commercially available which are specific for O_2, rugged and require little maintenance.

Recommendations for Tunnel Instrumentation

It is recommended that measurement of CO in tunnels be continued on a routine basis. For both manned and unmanned tunnels, the Hopcalite-type device should serve as a reliable means of monitoring CO concentration. In the case of automatic control of tunnel ventilation equipment, the NDIR or Hopcalite instrument can be used to control ventilation rates.

If the tunnel air is to be recycled, the NDIR type of instrument should be used since a lower level of detection can be attained and the response time is better.

Monitors for smoke or haze should be installed in tunnels, particularly those subjected to heavy diesel traffic. At the present time no recommendations can be made on the specific type of instrument which should be used. Specific types of instruments should be tested under actual tunnel conditions with the objective being to select an optimum type of instrument.

CONCLUSIONS

As a result of this study on vehicular tunnel ventilation and air pollution treatment, the following conclusions have been made:

1. The major impurities in tunnels with respect to safety and comfort level are CO, NO_x, HC and particulates. CO levels may run as high as 350 ppm during rush hour traffic. NO_x and HC, particularly partially oxidized HC, are generally in the few ppm range, a level high enough to cause eye irritation and odor. Particulates have been found at the 2-5 mg/m^3 level which causes a reduction in visibility. Other impurities are present in tunnels but these are present at levels which are not harmful or irritating to the tunnel worker or transient. Lead and cadmium, two air contaminants which are of current concern with respect to public health and welfare, are orders of magnitude below the standard Threshold Limit Values.

2. Concentrations of various impurities as a function of vehicle velocity, type of vehicle, road gradient, ventilation rate and so on can be predicted by a computer model developed under this program. A copy of the program on punched paper tape has been delivered to DOT. The information derived from the model can be used to estimate ventilation requirements and to indicate optimized locations for tunnel impurity monitors.

3. Recommended limits for comfort and safety levels for CO, NO_x, HC and particulates have been set as a result of this study. These limits have been catagorized according to safety levels for manned and unmanned tunnels as well as comfort levels for unmanned tunnels.

Pollutant	Manned Tunnels	Unmanned Tunnels Safety Level	Unmanned Tunnels Comfort Level
CO	75 ppm	500 ppm	1000 ppm
NO	37.5 ppm	37.5 ppm	25 ppm
NO_2	10 ppm	5 ppm	1 ppm
HCHO	6 ppm	6 ppm	1 ppm
Particulates	10 mg/m^3	10 mg/m^3	N.R. (1)

(1) N.R. - No recommendation due to insufficient information.

The levels which have been selected are quite frequently exceeded in manned tunnels.

4. A review of the literature indicates that the technology exists to purify tunnel air either on a recycle basis or on a ventilation exhaust stack gas basis. Recommended methods include:

   CO - Catalytic combustion with Hopcalite at 250°F.
   NO_x - Conversion of NO to NO_2 by catalytic oxidation. Sorption of NO_2 on activated charcoal.
   HC - Activated carbon.
   Particulates - Electrostatic precipitation.

   Although this was a feasibility study rather than a design study, economic evaluation of the processes for the volume of gases to be handled, based on a hypothetical tunnel, indicates that both capital equipment costs and operating costs would be quite high and, that when possible, higher ventilation rates are the less expensive route to better tunnel air quality.

5. As has been done in the past, CO should be continuously monitored and used as an indicator for ventilation rates. Consideration should be given to the use of non-dispersive infrared CO monitors rather than the Hopcalite-type monitors because of the faster response and rise time of this type of instrument. In

addition to CO, smoke or haze should be monitored, also, particularly in those tunnels which have a heavy concentration of diesel traffic. Instrumentation would also be required if purification systems are used to assure that the various components of the system are functioning properly.

We believe there are three areas which require additional study:

1. Various smoke meters should be tested under actual tunnel conditions to establish the reliability of such instrumentation.

2. A prototype purification system should be tested under actual tunnel conditions to establish lifetime of the components and maintenance and replacement frequency.

3. Study of air recirculation at portals should be done to determine the extent of and means for minimizing or preventing recirculation.

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APPENDIX I

FINAL REPORT - INDUSTRIAL HEALTH FOUNDATION

FINAL REPORT

Subcontract No. D-24437
under
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TUNNEL VENTILATION AND AIR POLLUTION TREATMENT

Prepared for

MSA Research Corporation
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APPENDIX I

TABLE OF CONTENTS

		Page
I.	Introduction	212
II.	Work Statement	212
III.	Tunnel Pollutants	213
	A. Measured Concentrations in Tunnels	215
	B. Health Effects	216
	C. Other Physiological Effects	226
	D. Synergism	228
	E. Criteria for Recommending Limits	228
	F. Time-Concentration Effects	230
IV.	Conclusions and Recommendations	231
V.	References Cited	237

List of Tables

Table 1 - Emission Factors	213
Table 2 - Automobile Exhaust Products	214
Table 3 - Exhaust Gas Analysis	214
Table 4 - Exhaust Constituents	215
Table 5 - Measured Tunnel Contaminants	215
Table 6 - CO in Air and Toxic Symptoms	217
Table 7 - COHb and Symptoms	218
Table 8 - CO Time-Concentration-Effect	218
Table 9 - Effects of NO_2 on Man	220
Table 10- SO_2 Concentration and Response	222
Table 11- Aldehyde Toxicity	223
Table 12- Tunnel Contaminants vs Existing Limits	232

List of Illustrations

Figure 1 - CO Exposures and Effects	235
Figure 2 - Percent COHb (CO Time-Exposure Effect)	236

I. INTRODUCTION

This report represents a culmination of the efforts expended by Industrial Health Foundation's (IHF) staff personnel and science advisors in eliciting the physiological effects of atmospheric contaminants generated by vehicular traffic whether alone or in synergism and the relation of those effects with time-concentration exposures.

Wherever possible, criteria are developed for recommending desirable time-concentration limits along with the reasoning behind such criteria.

The bases are directed toward, but not necessarily limited to, effects on vehicular tunnel transient users and tunnel employees.

II. WORK STATEMENT

The work statement as described in the subject subcontract is quoted below:

A. Using its best efforts within the time and funds allotted, based on information provided by the Contractor, the Subcontractor will classify each impurity generated by vehicular traffic into a category which will identify the effect of each impurity upon the various tunnel users, i.e., transients as well as maintenance personnel. For each, the degree of toxicity, irritation and visibility reduction shall be established with consideration of concentration levels and exposure times. An attempt will be made to rate odors in a relative basis. Typical impurities will include but not be limited to:

1. CO
2. CO_2
3. NO_2
4. Other oxides of nitrogen
5. Sulfates
6. Nitrates
7. SO_2
8. Aliphatic aldehydes
9. Polycyclic hydrocarbons
10. Particulates
11. Benzene soluble organics
12. Lead and other metals
13. Gasoline additives
14. Asbestos

B. The Subcontractor shall develop criteria for recommending desirable and allowable time concentration limits of the pertinent impurities for the maintenance of a safe and comfortable tunnel atmosphere for various conditions with due consideration to operating personnel as well as the traveling public. Reasoning behind the criteria shall be formulated.

C. Consideration should be given to the possible synergistic effects of one impurity in the presence of another impurity. The effect of pressure (sea level, 5,000 ft and 10,000 ft) shall be considered for those contaminants whose pulmonary behavior is dictated by pressure.

III. TUNNEL POLLUTANTS

The primary emphasis in determining the materials to be studied in this program is on those vehicular exhaust, blow-by and evaporative products emanating from both gasoline and diesel powered vehicles reported to be identified and measured in vehicular tunnels.

The secondary but also important consideration is the full spectrum of exhaust blow-by and evaporative products from gasoline and diesel motors whether in or out of vehicular tunnels.

There are several references to vehicular contribution to atmospheric pollution. Rossano[1] listed the emission factors for gasoline and diesel engines (in pounds per thousand gallons) (Table 1):

TABLE 1

Emission Factors

Pollutant	Gasoline Engines	Diesel Engines
Aldehydes	4	10
Benzo(a)pyrene	0.3 gm	0.4 gm
Carbon monoxide	2910	60 (a)
Hydrocarbons	524 (b)	180
Oxides of nitrogen	113	222
Oxides of sulfur	9	40
Ammonia	2	N.A. (c)
Organic acids	4	31
Particulates	11	110

(a) Includes blow-by emissions, but not evaporative losses
(b) Includes 128 lb/1000 gal. blow-by emissions
(c) Not available

Rossano's tabulation does not mention carbon dioxide, nitrogen, water vapor, oxygen or lead compounds as have been listed by Goldsmith and Rogers[2] who presented the automobile exhaust products (Table 2) as a per cent of concentration with minimum and maximum values.

TABLE 2

Automobile Exhaust Products

Constituent	Per Cent of Concentration (Vol./Vol.) Minimum	Maximum
Aldehydes	0.0	0.3
Carbon monoxide	0.2	12.0
Hydrocarbons	0.01	2.0
Oxides of nitrogen	0.0	0.4
Sulfur dioxide	See note 1	See note 1
Carbon dioxide	5.0	15.0
Hydrogen	0.0	4.0
Lead compounds	See note 2	See note 2
Nitrogen	78.0	85.0
Oxygen	0.0	4.0
Water vapor	5.0	15.0

1. Depends on sulfur content of fuel
2. Depends on lead additives

Atkinson et al[3] presented a tabulation (Table 3) showing exhaust gas analyses from gasoline and diesel engines, quoting from a Swiss report by Stahel et al, in undiluted exhaust.

TABLE 3

Exhaust Gas Analysis

	Gasoline	Diesel
Formaldehyde	7 ppm	11 ppm
Aldehydes	40	20
Carbon monoxide	30,000	200-1000
Oxides of nitrogen	600	400
Sulfur dioxide	60	200
Carbon dioxide	132,000	90,000

Caplan[4] presented a gas chromatographic analysis of exhaust gas hydrocarbons for a specific engine operating condition and fuel, primarily to exhibit the complexity of identification and potential effects. About sixty components are listed with approximate concentrations. Elliott et al[5] showed a list of constituents (Table 4) of internal combustion engine exhaust gases, divided into major (greater than 1%) and minor (less than 1%) constituents.

TABLE 4

Exhaust Constituents

Major	Minor
Water	Oxides of sulfur
CO_2	Oxides of nitrogen
N_2	Aldehydes
O_2	Organic acids
H_2	Alcohols
CO (a)	Smoke
	CO (b)
	H_2 (b)

(a) Spark ignition engine
(b) Diesel engine

A. Measured Concentrations in Tunnels

A compilation of contaminants measured in five tunnels was presented in the first quarterly progress report of this program (p. 11) by MSA Research Corporation.[6] The list is not complete and any attempt to compare the tunnels is inappropriate since the conditions under which the values were obtained were not comparable. The ranges of values measured for the contaminants are given in Table 5.

TABLE 5

Measured Tunnel Contaminants

Contaminant	
CO	54-170 ppm
NO_2	0.05-0.43 ppm
NO_x	0.2-1.63 ppm
Aldehydes	0.05-0.12 ppm
SO_2	0.04-<0.05 ppm
Total Particulates	0.424-2.350 mg/m^3
Polycyclic hydrocarbons	
Pyrene	0.04-1.20 $\mu g/m^3$
Benzo(a)pyrene	0.03-0.69 $\mu g/m^3$
Coronene	0.03-0.53 $\mu g/m^3$
Benzperylene	0.09-0.99 $\mu g/m^3$
Metals	
Lead	9.5-44.5 $\mu g/m^3$
Iron	9.5-23.4 $\mu g/m^3$
Zinc	2.2 $\mu g/m^3$
Cadmium	0.04-0.6 $\mu g/m^3$

Additional identified vehicular tunnel "pollutants" include carbon dioxide; anthanthrene; fluoranthene; several metals such as titanium, chromium, vanadium, nickel; asbestos and salts. Although not in the inventory of "chemical" pollutants, mention should be made here of noise and thermal pollution whether or not measurements of them have been documented.

B. Health Effects

The primary concern of the work scope of this effort is stated as the classification of each impurity generated by vehicular traffic to identify the effect of each impurity on the various tunnel users (transient and employed).

There is a wide variety of source material and information regarding health effects of many of the contaminants reported to be found in vehicular tunnels and those emanating from vehicles, resulting in a variety of versions. Unfortunately there are many voids in dose-response data. Hence, not all of the tunnel contaminants can be discussed with the same degree of confidence regarding their health effects. Later in this report we will attempt to develop time-concentration effects for as many of the "contaminants" as available information will allow.

1. Carbon Monoxide

There are many treatises on the subject of carbon monoxide, its health effects and its control in the literature. Sievers et al[7a,8] stated that examination of a group of one-hundred fifty-six Holland Tunnel traffic officers exposed throughout a period of thirteen years to an occupational CO exposure averaging 70 ppm did not reveal any evidence of injury to health attributable to carbon monoxide. Their eight-hour day was divided into alternating two-hour periods of service at tunnel exits or plazas and in the tunnel. For those who were non-smokers, data indicated that on the average 1.71 per cent of their hemoglobin was combined with carbon monoxide. For those who smoked more than one pack of cigarettes a day data indicated 5.35% of their hemoglobin combined with carbon monoxide. These were values for men who had not been on duty in the tunnel recently.

According to von Oettingen,[9a] Henderson et al gave a relationship between CO in the air and toxic symptoms (Table 6).

TABLE 6

CO in Air and Toxic Symptoms

CO (ppm)	
100	Concentration allowable for an exposure of several hours
400-500	Concentration which can be inhaled for 1 hour without appreciable effect
600-700	Concentration causing just appreciable effects after 1 hour of exposure
1000-1200	Concentration causing unpleasant but not dangerous symptoms after 1 hour of exposure
1500-2000	Concentration dangerous with exposure for 1 hour
4000 and above	Concentrations which are fatal in exposures for less than 1 hour

One of the initial symptoms of CO poisoning is headache which is associated sooner or later with irritability, fatigue and progressive weakness.

One of the most characteristic findings in acute CO poisoning resulting in unconsciousness is a complete amnesia for the time of the accident.

Psychoses as sequelae of CO poisoning have been observed repeatedly. Usually they develop after apparent recovery from the acute exposure. Despite some degree of controversy, evidence is lacking 1) that CO as such or in combination with other compounds remains in the tissue for any considerable time, and 2) that concentrations of CO which cause no acute subjective or objective symptoms will affect any structure of the organism in such a way as may lead to functional or permanent injury. It is generally believed that concentrations of up to 100 ppm of CO in air cause no subjective or objective toxic effects even with continued exposure. It has also been demonstrated that such exposure will not cause any signs or symptoms of chronic CO poisoning.(7a,7b,7c,8,9a, 9b,9c)

Carbon monoxide exerts its effects on man by combining with the hemoglobin of the blood and interrupting the normal oxygen supply to the body tissues. Although this resultant deficiency is a reversible chemical asphyxia, nevertheless, damage done by severe anoxia from any cause may not be reversible.(10)

Table 7 reflects the symptoms caused by various amounts of carbon monoxide hemoglobin in the blood.[10]

TABLE 7

COHb and Symptoms

Blood Saturation % CO Hemoglobin	Symptoms
0-10	No symptoms
10-20	Tightness across forehead, possible slight headache, dilation of cutaneous blood vessels
20-30	Headache and throbbing in temples
30-40	Severe headache, weakness, dizziness, dimness of vision, nausea, vomiting and collapse
40-50	Same as above, more collapse possibility, increased respiration and pulse
50-60	Above plus coma with intermittent convulsions
60-70	Above plus depressed heart action and respiration and possibly death
70-80	Weak pulse and slow respiration, respiratory failure and death

The degree of harm from carbon monoxide is a product of concentration times the length of exposure. Henderson and Haggard[11] proposed the following equation (Table 8) as a rough guide in estimating probable effects - it does not apply to exposures longer than a few hours.

TABLE 8

CO Time-Concentration-Effect

Hours X PPM	Effect
300	No perceptible effect
600	Just perceptible effect
900	Headache and nausea
1500	Dangerous to life

Satisfactory evidence has not been presented to indicate that any permanent ill effects in men or animals are to be expected from a single acute exposure to carbon monoxide where the exposed person or animal remains conscious throughout.[9a,9b,9c]

Figure 1 presents a series of curves, based on data in Table 8, which relate effects of CO with time and exposure level.

The signs and symptoms of acute CO intoxication only appear with carboxyhemoglobin (COHb) levels above 10%.[12] These levels are apparently hardly ever found in subjects exposed to traffic exhaust. Fisher and Hasse[13a] reported that in moderate CO poisoning produced by inhalation of CO in concentrations of 200 to 540 ppm over a period of 40 to 60 minutes, the labyrinth in most instances showed an increased excitability, as indicated by the lowering of the threshold for electric stimuli.

Zenk[13b] reported that "chronic carbon monoxide poisoning in twelve cases showed a slowly increasing hearing loss in the higher frequency areas".

Zorn[14] reported increased sensitivity to noise and increased psychic irritability in blast furnace workshops where CO exposure was experienced. Ten to twenty per cent COHb was measured. C.K. Drinker[15] reported dimness of vision above 1000 ppm for one hour associated with COHb greater than 30%. Petry[16] concludes from an extensive review of the world's literature that carbon monoxide doses below 50 ppm do not impair health. Miranda et al[17a] state that the effects of carbon monoxide from smoking and exposure to ambient carbon monoxide are <u>not</u> additive. If a person has 7% carboxyhemoglobin in his blood and is exposed to 25 ppm of CO, he will actually excrete CO. If exposed to 50 ppm, there will be no uptake, and if exposed to 100 ppm, the uptake will be quite slow.

The Aero Medical Association[17b] states that the tolerance for COHb in the blood is less at high altitude than at sea level; for example, 3% COHb at 15,000 feet produces effects equal to that caused by 20% COHb at sea level. A tabulation relating CO exposure concentration and time to reach 7% COHb at sea level when light work is being done showed 100 ppm requiring 88 minutes, 300 ppm requiring 29 minutes, and 500 ppm requiring 18 minutes to reach 7% COHb.

According to the Documentation for Short Term Exposure Limits,[18] a concentration of 1000 ppm CO could exist without creating physiologically unacceptable conditions when exposed to such a level for as long as ten minutes. This is roughly comparable to Henderson's equation.[11] Data in Reference 18 relate carboxyhemoglobin levels with CO concentrations and exposure time. They are consistent with data shown in Reference 17a in which equations are postulated for COHb determination and suggest that if the COHb level in the

person who is normally healthy is maintained below 14%, this is a physiologically acceptable level.

2. Nitrogen Dioxide

Adverse effects of exposures below 25 ppm have been reported by the Institute of Hygiene of Labor and Industrial Diseases, Leningrad, but our experience in the United States does not lend support to these findings.

Men observed working 6 to 8 hours daily in nitric acid recovery and fortification plants, where exposures ranged from 5 to 30 ppm and averaged 10 to 20 ppm, for periods up to 18 months, evidenced no significant ill health nor were any characteristic adverse effects detected by periodic medical examinations.(10)

The odor of NO_2 is characteristic and distinct in concentrations as low as 5 ppm. In concentrations of 10 to 20 ppm the gas is mildly irritant to the eyes, nose and upper respiratory mucosa. Concentrations considered dangerous for short exposure, i.e., above 50 ppm, are moderately irritating to the eyes and nasal passages. Higher concentrations, up to 150 ppm, cause an acid taste but are not painfully irritant.

The Association of Casualty and Surety Companies (Chemical Hazard Bulletin) states that 10 to 20 ppm can be endured with no discomfort.

The Los Angeles County Air Pollution Control District established a concentration of 3 ppm for the first alert, 5 ppm for the second alert, and 10 ppm for the third alert.(19)

Cooper et al,(20) in reviewing literature on the effects of NO_2 on man, developed a tabulation which is abstracted in Table 9. They also state that there is no evidence for any carcinogenic effects of NO_2 in man and that there is too little evidence on which to base any conclusions regarding NO_2 adsorbed on particulates. They conclude that this is an area requiring long-term research experiments before any definitive data will be available.

TABLE 9

Effects of NO_2 on Man

PPM	Effect or Comment
0.2	Calculated limit for space travel
0.5	Submarine maximum for 90 day dive
1-3	Odor threshold

TABLE 9 cont.

Effects of NO_2 on Man

PPM	Effect or Comment
5	Threshold limit for occupational exposure (8 hr day, 5 day wk)
5	Exposure of one asthmatic and one pilocarpinized volunteer for five minutes; no effects noted
10	60 Minute emergency exposure level for occupational exposure
10	Maximum permitted in submarine for one hour
10	Normal volunteers exposed for 60 minutes - not showing pulmonary function impairment
13	8 Volunteers: 3 had eye irritation; 7, nasal irritation; 4, pulmonary discomfort; 6 olfactory cognition; all predominantly slight
20	Workers in HNO_3 recovery plants reportedly exposed to levels averaging up to 20 ppm for up to 18 months showed no ill effects
20	Emergency exposure limit for 30 minute exposure
25	Emergency exposure limit for 15 minute exposure
30-35	Workers exposed in 30-35 ppm of nitrous gases over several years had no ill effects
35	Emergency exposure level for 5 minutes
50	7 Human volunteers exposed for one minute; 3 had pulmonary discomfort and nasal irritation
80	In 3 to 5 minutes volunteers got tightness of the chest
100	Produced marked irritation of larynx and cough in volunteers
300-400	Few minutes exposure will cause bronchopneumonia and death

In animal research Gross et al[21] concluded that long-term exposure of hamsters to NO_2 did not cause emphysema at an average concentration of 22 ppm (ranging from 10 to 34 ppm) exposed for two hours per day, five days per week for three consecutive weeks.

3. Sulfur Dioxide

Sulfur dioxide is an irritant gas; 6 to 12 ppm causes immediate irritation to nose and throat. About 20 ppm is the least amount irritating to the eyes.[10] Its inhalation affects chiefly the upper respiratory tract, trachea and bronchi. The strong sensory stimulation often causes spasm of the glottis, which protects the deeper passages. Recovery from the effects of short exposure is rapid.[22]

Association of Casualty and Surety Companies (Chemical Hazards Bulletin 1952) show the data in Table 10.[18]

TABLE 10

SO_2 Concentration and Response

SO_2-PPM	Response
3-5	Least detectable odor
8-12	Least amount causing immediate throat irritation
10	Maximum concentration allowable for prolonged exposure
20	Least amount causing coughing and immediate eye irritation
50-100	Maximum concentration allowable for 1/2 to 1 hour exposure
400-500	Dangerous for even short exposures

Sim and Pattle[23] reported that with dosages equivalent to 30 ppm for 10 minutes little change was noted either clinically or by measurement of lung resistance to air flow. With dosages of 50 ppm for 10 minutes the lung resistance increased significantly above normal in 50% of the people exposed.

Battigelli[24] states that "populations exposed to SO_2 at significant levels, ranging from 0.5 to 2 ppm and even higher, do not present direct evidence of increased susceptibility to respiratory infection deriving from the effects of SO_2. Industrial experience provides a definite negative reply. The search for an acceptable rationale, or for reasonable evidence documenting a toxicological relevance of SO_2 levels, as these are encountered in urban air pollution, has thus far failed. If urban pollution has a measurable effect on the health and disease of exposed populations, as it appears to have, on the basis of available information, this phenomenon does not appear to involve SO_2 in its mechanism".

SO_2, in its various forms and metabolic products, does not accumulate in the human system and does not accumulate in the atmosphere.[25] There is a threshold level below which no detectable response to SO_2 that might conceivably be health-related occurs. This threshold response is 1 to 2 ppm in the most sensitive individuals.

4. Aliphatic Aldehydes and Formaldehyde

Formaldehyde and acrolein have been identified as

components of automobile exhaust fumes. Others may be present such as crotonaldehyde and saturated aldehydes.

In general, the toxicity of the saturated aldehydes decreases with increasing molecular weight. The unsaturated aldehydes are extremely irritating. The irritant nature of aldehydes, from human experience, provides sufficient warning to prevent serious health effects. This may explain the paucity of information regarding the experimental toxicology of chronic aldehyde exposure.[26]

The systemic toxicity of formaldehyde is relatively low. It irritates the mucous membranes via hardening the tissues on local contact. All organic aldehydes are reported to be irritant. The toxic effects of acrolein consist chiefly in strong irritation of the skin and exposed mucosae. No other chronic ill effects have been reported.[22]

The relative acute toxicity of aliphatic aldehydes tabulated by Skog, reported in reference 26, is shown in Table 11.

TABLE 11

Aldehyde Toxicity

Aldehyde	Rat Inhalation LC_{50} (ppm) (30 min)
Acrolein	131
Formaldehyde	815
Crotonaldehyde	1,396
Acetaldehyde	20,572
Propionaldehyde	26,164
Butyraldehyde	59,160

In the experience of Barnes and Speicher[27] exposure to 20 ppm of formaldehyde produced lacrimation in 15 to 30 seconds, irritation of the nose and throat at the end of 30 seconds, and sneezing in 1 or 2 minutes.

Sim and Pattle[23] exposed human volunteers to vapors of several aldehydes for from 5 to 30 minutes. Formaldehyde caused irritation of mucous membranes and lacrimation at 13.8 ppm; acrolein was violently irritating and lacrimatory at .8 and 1.2 ppm, crotonaldehyde was irritant and lacrimatory at 4.1 ppm; acetaldehyde produced slight irritation to the upper respiratory tract at 134 ppm; propronaldehyde, butyraldehyde and isobutyraldehyde were non-irritating at concentrations of 134 ppm, 230 ppm and 207 ppm, respectively.

Henderson and Haggard[11] state that 1 ppm acrolein in air is immediately detectable, that 5.5 ppm causes intense irritation and that 10 ppm is lethal in a short time.

Elkins[28] reports that 5-6 ppm causes eye irritation in persons acclimatized to formaldehyde and at lower concentrations in those not acclimatized. Five ppm prevents respiratory injury, but not irritation. Cases of itching eyes have been noted at concentrations of 1 to 2 ppm.

5. Hydrocarbons

Hydrocarbons represent the most complex exhaust emission class. However, in terms of quantitative emissions, hydrocarbons are a relatively small emission component.[4]

Methane, ethane, propane, ethylene and acetylene, all of which are classified as biologically inert gases, comprise a substantial portion of hydrocarbon emissions. Pentane and hexane, which are also reported to be a substantial portion of automotive hydrocarbon emission, produced no symptoms in man exposed for ten minutes to 2,000 ppm.[10]

Concern has been expressed in many quarters about the polycyclic hydrocarbon content of automotive exhaust emissions. Hoffman et al[29] report that the major carcinogenic activity in gasoline exhaust tar is due to the four, five and six ring aromatic hydrocarbons.

Although polycyclic hydrocarbons produce tumors when painted on the skin of susceptible animals, their inhalation has resulted in no experimental lung cancer.[2]

6. Metals[10]

A variety of metals have been reported as having been found in vehicular tunnel atmospheres, all in $\mu g/m^3$ quantities. Their physical nature has not been elicited, but none of those reported even approaches the TLV (time-weighted average for eight hours per day, five days per week, exposure).

a. Cadmium - Prolonged (1 year) inhalation of CdO and CdS, separately, by dogs at levels of 3 to 7 mg/m^3 daily resulted in no damage. As little as 14.5 mg of Cd taken orally by man has caused nausea, but as much as 326 mg was not fatal. The estimated time-concentration LC_{50} for dogs is 4000 mg min/m^3.

b. Chromium - Chromium salts, including Cr_2O_3, are ascribed a low order of toxicity and have caused no significant industrial illness. On the other hand, chromates are reported to be systemically toxic and carcinogenic.

c. Copper - Repeated exposure to Cu fume levels up to 400 $\mu g/m^3$ caused no complaints and brief exposures to concentrations of 1 to 3 mg/m^3 resulted in no other discomfort than a sweet taste.

d. Iron - Siderosis, or iron pigmentation, is reported to occur at exposure levels above 10 mg/m^3 of Fe oxide fume, which is a relatively low order of toxicity. Physical examinations and tests of work capacity of welders with Fe pigmentation show that it causes little or no disability.

e. Nickel - Apart from the possible malignant effects of nickel carbonyl, dermatitis constitutes the only other serious nickel exposure hazard.

f. Titanium - The physiological history of TiO_2 is one of inertness. No significant pulmonary alterations were observed among workmen employed in enclosed workshops with TiO_2 dust.

g. Vanadium - In a study to test experimentally in animals the suitability of a threshold limit for V_2O_5 of 500 $\mu g/m^3$ recommended by the Russians, it was found that dogs, rats, guinea pigs, and rabbits tolerated V_2O_5 dust exposure at this level for 6 months of daily 6-hour exposures without evidence of histological change referable to inhalation of the dust.

No effects except lowered serum cholesterol levels were seen among vanadium processing workers in Colorado who were exposed to vanadium levels of from 100 to 300 $\mu g/m^3$.

h. Lead - Inorganic lead has not been reported as a cause of acute reactions even at the highest airborne concentrations. No harmful effects to humans have been reported at the highest ambient concentrations. "Measured concentrations of organic lead are very low, so low in fact that it is not necessary to consider organic lead as a practical constituent of the atmosphere."[30]

7. Particulates

Hoffman et al[29] discussed the analysis of the exhaust tar from gasoline engines. Among about 30 isolated and identified polynuclear aromatic hydrocarbons (PAH) were

10 components which are carcinogenic to the experimental animal. It must, however, be here reiterated, as stated by Goldsmith and Rogers,[2] that carcinogenic activity has only been detected with dermal application. No experimental lung cancer has resulted from inhalation of these compounds. Lyons[31] reported PAH compounds in diesel exhausts of which several are reportedly carcinogenic to experimental animals via dermal application.

Waller et al[32] made observations on the size and shape of particles in the atmosphere of London and a number of samples were collected in the Blackwall Tunnel. Nearly all the particles were small smoke aggregates, with a mass median diameter of 1 micron. The forms were typical of those produced by the incomplete combustion of hydrocarbon fuels. All were small enough to stay in suspension indefinitely and they were well within the respirable size range. The maximum concentration of smoke occurs when the number of diesel vehicles is highest.

C. Other Physiological Effects

1. Irritation

Eye irritation is by far the most noticeable and obnoxious symptom of smog as far as the public is concerned. The identity of the exact compounds produced in smog reactions, which are responsible for eye irritation, have not been established. Formaldehyde, acrolein, and peroxyacyl nitrate (PAN) have been variously reported as being involved, but there is no general acceptance of this. Actual measurements in the Los Angeles atmosphere have failed to demonstrate that such compounds are present in sufficient amounts, alone or together, to cause eye irritation.[33]

Oxides of nitrogen are suspected of contributing to eye irritation caused by vehicular exhaust but insufficient specific information has been developed to formally indict them.

The low molecular weight aldehydes, formaldehyde and acrolein, cause eye reaction at as low as 0.01 ppm exposure level, which is below the odor threshold for both. However, acrolein produces only mild sensory irritation at 0.25 ppm while formaldehyde produces mild irritation of the eyes and nose at 2 to 3 ppm. The higher aliphatic aldehydes have much higher irritation thresholds.

Aromatic hydrocarbons (benzene, toluene, xylene, etc.) can cause irritability but not without chronic exposure or relatively high acute exposure.

Exposure to the levels of paraffin hydrocarbons found in automotive exhausts, particularly in vehicular tunnel atmospheres, are likely to be entirely free from any irritant effect. The oxides of sulfur may cause throat irritation, but such is not likely to be encountered in tunnel atmospheres unless there is a significant build-up of oxides of sulfur. The same may be said for oxides of nitrogen.

Carbon monoxide, while not an irritant in the true sense can cause headache and irritability.

Carbon dioxide, which has not heretofore been mentioned in this report, is a product of automotive exhaust. Its only significant effect, if in large enough concentration, is as a toxicant contributor to respiration difficulty and as such could add to the respiratory burden of ill persons. Such levels are virtually impossible to attain in tunnel atmospheres.

Information on irritant effects, other than dermatologic, of polycyclic hydrocarbons is inconclusive and insufficient on which to base any comment.

2. Odor

There have been many conflicting reports related to the specific sources and causes of odors which have been purported to result from vehicular exhaust, to the point that there appear to be more areas of lack of agreement than of agreement. For example, acrolein and formaldehyde, which do have low odor thresholds, have been cited as contributors to automotive exhaust odors. The odor threshold for formaldehyde is reported to be from 0.05 to 1.0 ppm while for acrolein it is reported to be from 0.21 to 1.8 ppm, depending on the source.(34)

The present state of knowledge is too scanty and contradictory to utilize the available data on odor thresholds with any degree of confidence.

The odor of NO_2 is characteristic and distinct in concentrations as low as 5 ppm. SO_2 has an easily noticeable odor at 3 ppm, while some can detect at concentrations as low as 0.3 ppm (probably more by taste than by odor). CO, of course, is odorless.

Because of the chemical complexity of the particulates, odor is not a likely means of identification nor would it be one of the attributes to consider controlling.

3. Visibility

Addressing these remarks to vehicular tunnel atmospheres, we can for the most part ignore photochemical smog because of the minimum amount of radiant energy available. The visibility problem(s) then relate to clarity of the atmosphere, i.e., suspended particulates (smoke) and those tunnel contaminants which affect visual acuity, whether through lachrimatory or other processes.

Concerning particulates, not only do they alone contribute to visibility reduction, but the added effect of droplets (vapors) of the oxides of nitrogen, the oxides of sulfur and the unburned hydrocarbons from blow-by, evaporation and incomplete combustion contribute to a haze effect.

Reduction of particulates, which in themselves may not be significant health hazards, would reduce the "plating out" effect of vapors on them.

D. Synergism

The first thought might well be photochemical reactivity, but in tunnel atmospheres this is minimized.

There are, however, interacting forces, as for example the effect of carbon monoxide on normally healthy tunnel users or employees vs. the effect of CO on heavy smokers and/or on those who have cardiopulmonary deficiencies. Additionally, there can be the effect of humidity on the exhaust products and their relative toxic, irritant or nuisance value, and the difference in effects of exhaust emissions at or near sea level vs. those at higher elevations. Although not chemical pollutants, both noise and temperature can have effects on tunnel users and employees.

It has been reliably reported that carbon monoxide is not oxidized by ozone at ordinary temperatures.[35]

E. Criteria for Recommending Limits

There are several bases for concern and consideration of desirable improvements in the ambient atmosphere in operative vehicular tunnels: health, safety, comfort, traffic flow, maintenance, disaster control, ease of facility design and construction, effect on the outside atmosphere, aesthetics and economics, and perhaps others.

There are probably as many defensible ways to rank these bases as there are people of differing backgrounds and interests who set themselves to the task of such ranking.

The rationale used in our deliberations is that the health of the transient users and of the tunnel work force are necessary prerequisites to virtually all the others. If these are considered as the top priority and are adequately effected, then safety and disaster control will be more readily effected as second priority subjects. If the second priority items are well under control, then maintenance of the tunnels and traffic flow will be made easier as third priority considerations. It is difficult to divorce economics from any of the bases because of the obvious and necessary intermeshing. Consequently, economics, although here relegated to a relatively low order of priority, must be considered along with each of the concerns here listed.

Closely related to economics is the ease of facility design and construction, whether it is to improve existing tunnels or to construct new tunnels.

While comfort and aesthetics are quite desirable, they are assigned the lowest priority of those elements of concern in this listing since their consideration and implementation will require the utilization of funds which must first be earmarked for concerns of higher priority.

Based on an extensive review of literature and data, both published and unpublished, there are several gaps in information and data which preclude any possibility of recommending unequivocal criteria for setting limits or establishing standards for vehicular tunnel atmospheres.

Throughout this report, reference has been made frequently to threshold limit values, short term limits, contaminant concentrations in parts per million, milligrams per cubic meter or micrograms per cubic meter. There have been references to measured as well as to estimated values. Not all the values are readily comparable one with the other since the bases for establishing limits, for example, are quite different even within the same set of limits such as TLV's.

Consequently, any attempt to develop time-dose relationships for tunnel contaminants will of necessity be empirical at best and of extremely limited use.

A representative example will show this problem quite clearly. There have been proposed for carbon monoxide a threshold limit value, short term limit and emergency exposure limits by the Pennsylvania Department of Public Health.

CO: TLV = 50 ppm (8 hr day - 5 day week)
STL = 400 ppm (15 minutes)
EEL = 400 ppm (60 minutes)
" = 800 ppm (30 minutes)
" = 1500 ppm (10 minutes)

The TLV and STL are purportedly safe limits which will result in no deleterious health effects to the normal person. They do not take into account those people who have health deficiencies.

The EEL values were established for military and space short term inhalation standards at which some degree of intoxication, though temporary, may result.

F. Time Concentration Effects

A reasonably valid assumption is that, for transient tunnel users and for tunnel employees who alternate periods of work in the tunnel with periods of work outside the tunnel, if the pollutant concentration in the tunnel does not exceed the TLV for that pollutant, the probability of no adverse health effect from that pollutant is very high.

We may go further and assume that normally the short term limits can apply as far as transient users of the tunnels are concerned. However, here we may be assuming too much if there are long traffic delays which would exceed the short term limit period.

The Community Air Quality Guides for Aldehydes[34] presents a series of concentrations for formaldehyde and the effects experienced. Comparing them with TLV and STL, we find the following:

HCHO: TLV 5 ppm
STL 5 ppm (5 minutes)
AQG 2-3 ppm - repeated 8 hour exposures; mild irritation; discomfort
4-5 ppm - tolerate up to 30 minutes; lachrymation
10 ppm - borne with difficulty; profuse lachrymation

Here again, any attempt to develop meaningful time-concentration relationships is fraught with hazard and uncertainty.

Figures 1 and 2 are graphic representations of data concerning time-concentration relationships for carbon monoxide. Even here the data in the literature are not fully consistent.

The most useful available data regarding tunnel contaminants and possible limit levels are those shown in Table 12. By reviewing the data in this table, we can assign at least preliminary priorities to those pollutants which approximate or exceed the TLV's, namely, carbon monoxide and total particulates. The remainder are far below TLV's and are least likely to be major health concerns if CO and particulates are reduced, controlled and/or eliminated. NO_2 would be the third candidate to control or reduce.

IV. CONCLUSIONS AND RECOMMENDATIONS

One of the hoped for goals of this program was the development of criteria for tunnel air quality standards. Based on the information and data available, our society is not equipped to establish tunnel air quality standards because of lack of adequate information on which to base them.(36) We must carefully consider the purpose of standards, what they represent, how they are intended to be used, if they will accomplish their purpose, and what unexpected problems may develop from them. We must also consider the monitoring program required to implement the standards; not all of the many complex factors concerning standards establishment can be readily resolved.(37) Many questions now remain unanswered which preclude reasonable, rational, defensible, and practical standards development. If and when standards are established, they must be easily revised as experience and new information dictate.

In summarizing important engineering developments from 1965-68, (in Volume 1 of Industrial Hygiene Highlights) Bloomfield quotes and endorses Miranda as follows:

> "High altitude, coupled with the presence of carbon monoxide, serves to deprive the blood of its oxygen carrying capacity. An evaluation of the physiologic and ventilation control problems associated with a 1.6 mile tunnel at an elevation of 11,000 feet was made in order to develop recommendations concerning tunnel ventilation and tunnel use.
>
> It was recommended that:
>
> 1. The CO concentration in the tunnel be maintained below 25 ppm with one hour averages no higher than 50 ppm, and short term peaks no higher than 75 ppm.

TABLE 12

TUNNEL CONTAMINANTS VS EXISTING LIMITS

Contaminant	Contaminants Measured in Tunnels	TLV ppm/8 hrs	STL ppm/minutes
CO	54-170 ppm	50 ppm	400/15 200/40 100/180
NO_2	.05-.43 ppm	5 ppm	25/5
N_2O) NO)	.2-1.63 ppm	Simple Asphyxiant 25 ppm	NA NA
Aldehydes Formaldehyde Acetaldehyde	.05-.12 ppm	2 ppm* 200 ppm	5/5
SO_2	.04-<0.5 ppm	5 ppm	20/5
Pyrene	.04-1.20 $\mu g/m^3$	200 $\mu g/m^3$	NA
Benz(a)pyrene	.03-.7 $\mu g/m^3$	200 $\mu g/m^3$	NA
Coronene	.03-.53 $\mu g/m^3$	NA	NA
Benzperylene	.09-.99 $\mu g/m^3$	NA	NA
Lead	9.5-44.5 $\mu g/m^3$	200 $\mu g/m^3$	NA
Iron	9.5-23.4 $\mu g/m^3$	10,000 $\mu g/m^3$	NA
Zinc	2.2 $\mu g/m^3$	1,000 $\mu g/m^3$	NA
Cadmium	.04-.6 $\mu g/m^3$	100 $\mu g/m^3$	NA
Total Particulates	.42-2.35 mg/m^3	5 mg/m^3 (oil mist particulate) 3.5 mg/m^3 (carbon black)	

NA = Not available
* = Recommended revised ceiling

2. Signs be placed on the route to warn sensitive individuals of the dangers of high elevations and smoking and to suggest possible alternate lower routes.
3. Oxygen masks be provided at the tunnel for emergency use.
4. Construction workers involved in building the tunnel be screened for cardiopulmonary abnormalities, as well as blood dyscrasias (sickle cell anemia). They should also be acclimatized to the high altitude through progressively increased exercises."(38)

An additional practical and easy to adopt measure would be installation of an audio-visual warning (based on either CO quantitation or SOP or both) which would require turning off auto ignition in case of traffic stoppage.

There are certain other methods for improvement in tunnels also to be considered, either for existing or new tunnels:

1. Pre-employment physical examinations for tunnel employees and frequent periodic physical examinations to document any or no changes.

2. Develop traffic control systems which will activate during serious traffic tie-ups or tunnel area disasters.

3. Develop driver education programs for sound guidance specifically for tunnel traffic driving.

4. Develop improved methods for detecting pollutants, identifying and quantifying them.

5. Develop appropriate research programs to fill the gaps and to determine the effects of several levels of pollutant concentrations for several time periods.

6. Develop appropriate research programs to determine the nature and extent of synergistic effects.

7. Develop suitable methods for reducing suspended particulates in tunnels.

8. Determine the true priorities for tunnel atmosphere improvement considering health, safety, engineering design and maintainability.

9. Initiate a program to determine the accident rates in tunnels over an extended period of time with particular emphasis on the causes of the accidents.

10. Initiate a program to determine the contribution of tunnel equipment, materials and road bed erosion to the pollutant inventory.

11. Study the tunnel lighting to consider the optimum lighting for users and employees.

Undoubtedly, the 1971 Automotive Air Pollution Research Symposium sponsored by the Coordinating Research Council, Inc., on May 3-5, 1971, at the Ambassador West Hotel, Chicago, Illinois, will present additional data and concepts which should be taken into consideration when they become available along with the contents of this report.

FIGURE 1 - CO EXPOSURES AND EFFECTS

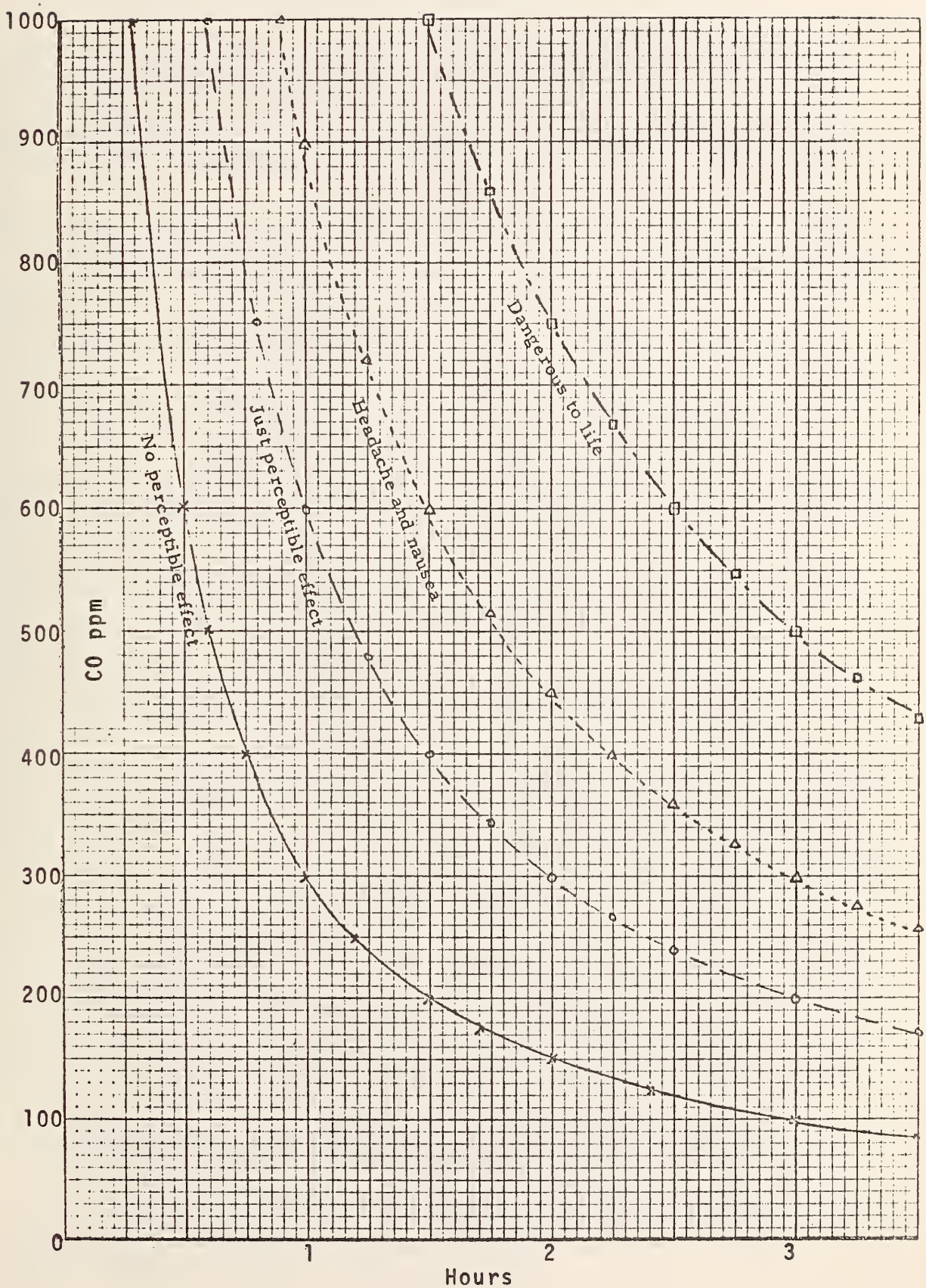
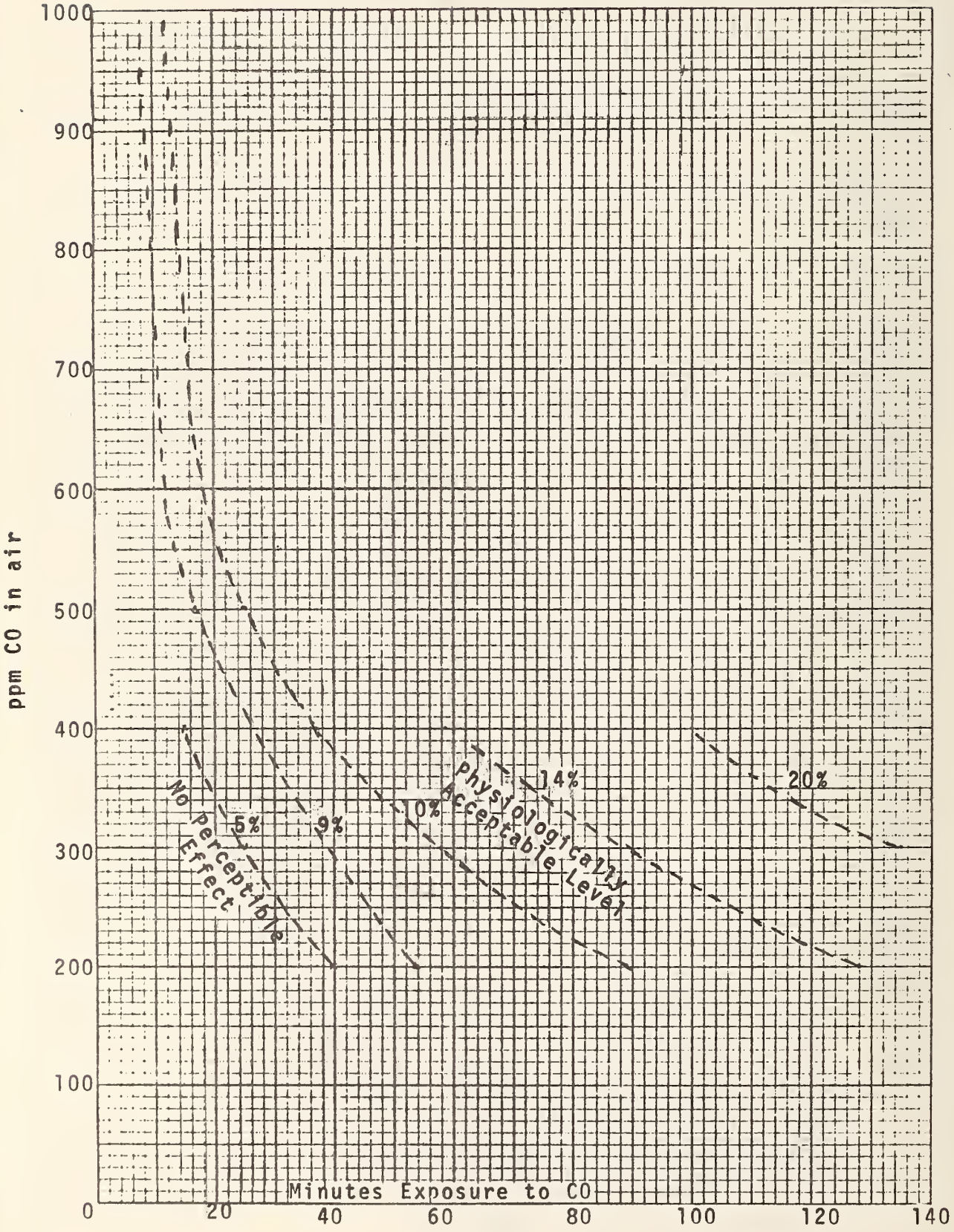


FIGURE 2 - PERCENT COHb (CO TIME-EXPOSURE EFFECT)



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APPENDIX II

Pollutant Removal Process Calculations
from Final Report - Patent Development
Associates, Inc. (See page 81)

APPENDIX II

TABLE OF CONTENTS

		Page
I.	Calculations of Average Emissions of CO and Hydrocarbons from Automobiles in 1970, 1975, and 1980	243
II.	Thermal Incineration	246
III.	Spray Chamber Calculations: Particulate Removal	247

List of Illustrations

Figure 1 -	Pressure Drop Through Carbon Beds	250
Figure 2 -	n-Butane Adsorption Isotherm on BPL Carbon	251

I. CALCULATIONS OF AVERAGE EMISSIONS OF CO AND HYDROCARBONS FROM AUTOMOBILES IN 1970, 1975 AND 1980.

A. Automotive age percentiles calculated from Blum (1967).

B. Emission data taken from Air Pollution, Vol. III, A.C. Stern (ed.) p 76, (1968).

YEAR 1970

1970 AUTOMOBILE POPULATION:

Vehicles 1954 to 1964 - 63.40% with emission standards of:

HC = 900 ppm CO = 32,000 ppm

Vehicles 1964 to 1969 - 36.60% with emission standards of:

HC = 275 ppm CO = 15,000 ppm

therefore, average automobile exhaust during 1970 will have:

$$HC = 900 \times 0.634 + 275 \times 0.366$$

$$= 560 + 100$$

$$= 660 \text{ ppm}$$

$$CO = 32{,}000 \times 0.634 + 15{,}000 \times 0.366$$

$$= 20{,}300 + 5{,}466$$

$$= 25{,}790 \text{ ppm}$$

YEAR 1975

1975 AUTOMOBILE POPULATION:

Vehicles 1959 to 1964 - 17.08% with emission standards of:

HC = 900 ppm CO = 32,000 ppm

Vehicles 1965 to 1969 - 46.32% with emission standards of:

HC = 275 ppm CO = 15,000 ppm

Vehicles 1970 to 1974 - 36.60% with emission standards of:

HC = 180 ppm CO = 10,000 ppm

therefore, average automobile exhaust during 1975 will have:

HC = 900 x 0.1708 + 275 x 0.4632 + 180 x 0.366

= 153 + 127 + 68

= 348 ppm

CO = 32,000 x 0.1708 + 15,000 x 0.4632 + 10,000 x 0.366

= 5,460 + 6,950 + 3,660

= 16,070 ppm

YEAR 1980

1980 AUTOMOBILE POPULATION:

Vehicles to 1964 - 1.34% with emission standards of:

HC = 900 ppm CO = 32,000 ppm

Vehicles 1965 to 1969 - 15.74% with emission standards of:

HC = 275 ppm CO = 15,000 ppm

Vehicles 1970 to 1974 - 46.32% with emission standards of:

HC = 180 ppm CO = 10,000 ppm

Vehicles 1975 to 1979 - 36.60% with emission standards of:

HC = 50 ppm CO = 5,000 ppm

therefore, average automobile exhaust during 1980 will have:

HC = 900 x 0.0134 + 275 x 0.1574 + 180 x 0.4632 + 50 x 0.3660

$$= 12 + 43 + 83 + 18$$

$$= 156 \text{ ppm}$$

$$CO = 32{,}000 \times 0.0134 + 15{,}000 \times 0.1574 + 10{,}000 \times 0.4632 + 5{,}000 \times 0.3660$$

$$= 430 + 230 + 4{,}630 + 1{,}830$$

$$= 6{,}120 \text{ ppm}$$

II. THERMAL INCINERATION

Based on HEW, AP-51

Assume Direct Flame, with Heat Exchange

Annual Capital Charge

Installed Cost (with Exchanger) = $220,000
Annual Capital Charges = (0.133)($220,000)
= $29,260

Annual Operating & Maintenance Charges (G)

$G = S[195.5 \times 10^{-6} PHK + M + HF]$

	Value
S = Design Capacity, CFM	250,000
P = Gas pressure drop, inches of H_2O	1
H = Annual operating hours	4,380
K = Power costs, $/kw-hr	0.011
M = Maintenance cost, $/ACFM	0.06
F = Fuel Cost, $/Hr/ACFM	0.23/1000

$G = 250,000 [(195.5 \times 10^{-6})(1)(4,380)(0.011) + 0.06 + (4,380)(0.23/1000)]$
$= 250,000 [1.0768]$
$= \underline{\$269,200}$

Total Annual Cost = $29,620 + $269,200
= $\underline{\$298,460}$

Major part of operating cost is in fuel cost.

III. SPRAY CHAMBER CALCULATIONS: PARTICULATE REMOVAL

Spray density - 20 lb water/100 cu ft air
Water droplet size - 500 microns
Particulate size - 1 to 5 microns
Removal efficiency - (a) 90%
(b) 75%

Nomenclature

ρa = density of air at 70°F

ρw = density of water at 70°F

ρp = density of particulate

μ = viscosity of air

D_p = diameter of particulate, cm

D_c = diameter of collector drop, cm

C = drag coefficient

v = terminal velocity of spherical particle settling in air at 70°F, cm/sec

Ψ = inertial parameter

t = holdup time, sec

N = concentration of spray droplets per unit volume of air

η = efficiency of impaction

$\frac{n}{no}$ = fraction of particles remaining

N = concentration of spray droplet/unit volume of air

$$= \frac{20 \text{ lb water}}{1000 \text{ cu ft air}}$$

$$= \frac{20 \text{ lb} \times 454.5 \text{ gm/lb}}{1000 \text{ cu ft} \times 28317 \text{ cc/cu ft}}$$

$$= 3.14 \times 10^{-4} \text{ gm/cc}$$

Volume of one drop of water (500 microns in diameter)

$$= 1/6 \, \pi \, D_c^3$$

$= 6.55 \times 10^{-5}$ cc

Weight of one drop of water

$= 6.55 \times 10^{-5}$ cc $\times$ 0.981 gm/cc

$= 6.41 \times 10^{-5}$ gm

therefore:

$$N = \frac{3.14 \times 10^{-4}}{6.41 \times 10^{-5}} \text{ drops of water/cc of air}$$

$= 4.90$ drops of water/cc of air

CASE I: Dust Removal Efficiency = 90%

$$\frac{n}{no} = \frac{10}{100} = 0.1$$

For a unit volume of dusty air, the time rate of change of particle concentration in the spray region is:

$$\frac{dn}{dt} = nvN\eta\pi D_c^2/4$$

Integrating,

$$\frac{n}{no} = \exp(-tvN\eta\pi D_c^2/4)$$

$$\ln 0.1 = -2.05\ t\eta$$

$$\text{or } t = \frac{\ln 0.1}{-2.05\eta} = \frac{2.3026}{2.05\eta} = \frac{1.125}{\eta}$$

Terminal velocity, v, of spherical particle of unit density settling in air at 70°F

$= 213.4$ cm/sec

For spherical particle when terminal velocity is known

$$\frac{C}{Re} = \frac{4g\mu(\rho p - \rho a)}{3\rho^2 a\ v^3}$$

$= 0.0170$

From Perry, (1963)

$C = 1.24$ and $Re = 74.45$

Now, the inertial parameter, Ψ,

$$\Psi = \frac{C\rho p \; v \; D_p^2}{18\mu \; D_c}$$

$$\Psi = 1.63 \times 10^6 \; D_p^2$$

$$[\Psi]^{1/2} = [1.63 \times 10^6 \; D_p^2]^{1/2}$$

$$= 1.275 \times 10^3 \; D_p$$

D_p Microns		η, efficiency of impaction	$R = D_p/D_c$
1	0.1275	0	0.002
2	0.2550	0.07	0.004
3	0.3825	0.355	0.006
4	0.5100	0.54	0.008
5	0.6375	0.64	0.01

CASE II: Dust Removal Efficiency = 75%

$$\frac{n}{no} = \frac{25}{100} = 0.25$$

$$0.25 = \exp(-2 \; t\eta)$$

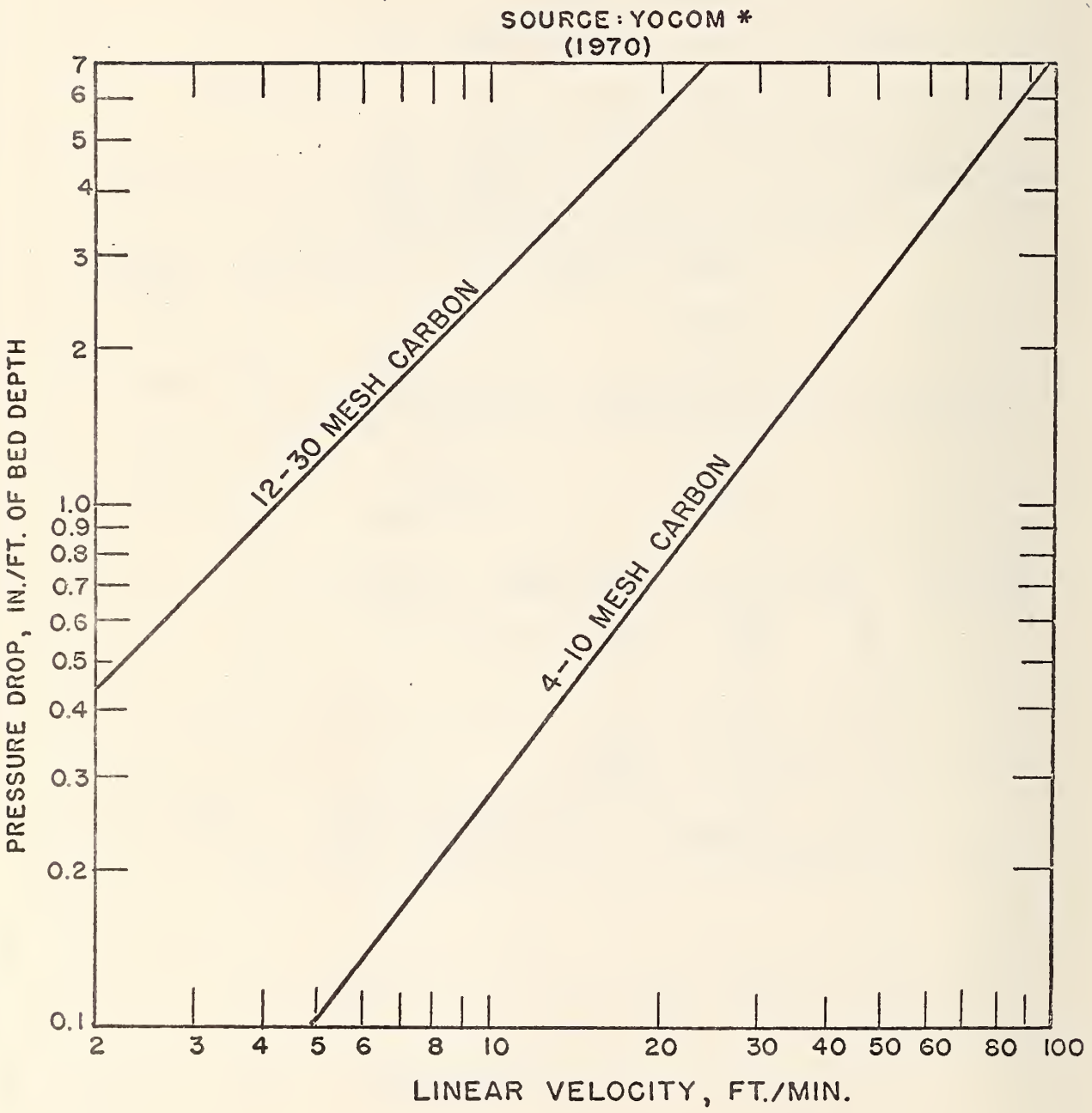
$$\text{or } \ln 0.25 = -2.05 \; t\eta$$

$$\text{or } t = \frac{\ln 0.25}{-2.05\eta} = \frac{2.3026 \times 0.6020}{2.05\eta} = \frac{0.68}{\eta}$$

FIGURE 1

PRESSURE DROP THROUGH

CARBON BEDS



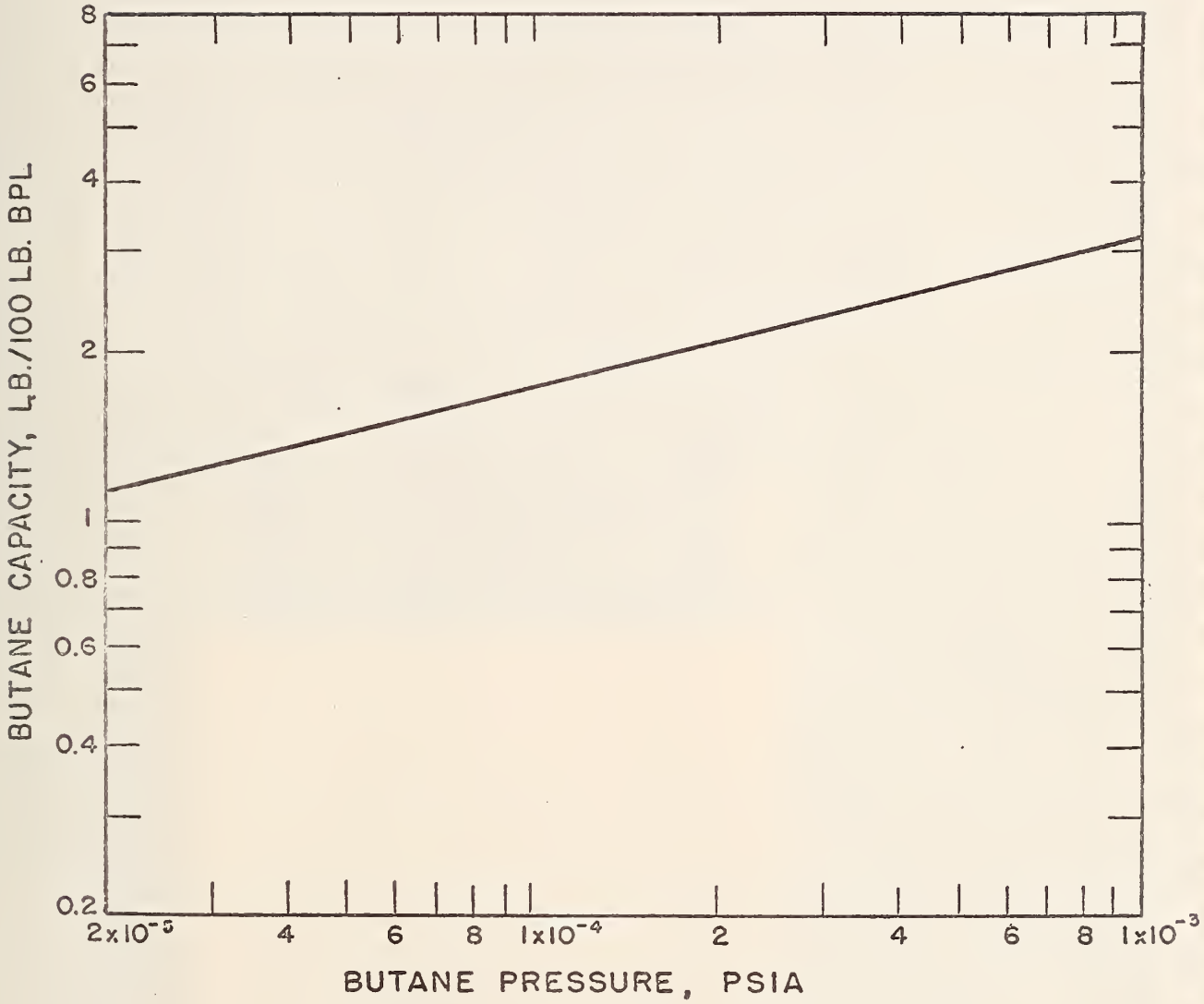
* Yocum, J. E. and Duffee, R. A., Chem. Eng. 77, No. 13, 160-168, June 15, 1970.

FIGURE 2

n-BUTANE ADSORPTION

ISOTHERM ON BPL CARBON

79°F.



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